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RAPID ADHESIVE BONDING CONCEPTS

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RAPID ADHESIVE BONDING CONCEPTS

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SUMMARY

Adhesive bonding in the aerospace industry typically utilizes autoclaves or presses which have considerable thermal mass. As a consequence, the rates of heatup and cooldown of the bonded parts are limited and the total time and cost of the bonding process is often relatively high. Many of the adhesives themselves do not inherently require long processing times. Bonding could be performed rapidly if the heat was concentrated in the bond lines or at least in the adherends.

Rapid Adhesive Bonding concepts have been developed at the NASA Langley Research Center to utilize induction heating techniques to provide heat directly to the bond line and/or adherends without heating the entire structure, supports, and fixtures of a bonding assembly. Bonding times for specimens can be cut by a factor of 10 to 100 compared to standard press bonding. This paper reviews the development of Rapid Adhesive Bonding for lap shear specimens (per ASTM D1003 and D3163), for aerospace panel bonding, and for field repair needs of metallic and advanced fiber reinforced polymeric matrix composite structures. Details of the equipment and procedures are described for bonding thin sheets, simple geometries, and honeycomb core panels. Test results are presented for a variety of

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adhesives and for specimens fabricated both with and without heating susceptors in the bond line. Lap shear strengths greater than 4000 psi for titanium adherends and greater than 3000 psi for graphite/epoxy composite adherends are routinely achieved.

The promise of advanced composite and bonded metallic structures for improvements in structural efficiency and cost is limited by current processing and repair technology. Rapid Adhesive Bonding concepts can advance that technology significantly.

INTRODUCTION

Adhesive bonding of metallic and fiber reinforced plastic composite structural components and specimens using thermosetting phenolic or epoxy adhesives is a widely used technology in the aerospace industry. Adhesive bonding is particularly important for joining composite materials because load transfer paths through mechanical fasteners (such as rivets or bolts) can cause local overloads and damage in the relatively brittle composites.

As indicated in references 1 to 4, the state-of-the-art for adhesive bonding with thermosetting adhesives is to surface treat and prime the adherends, carefully place an adhesive film or fiberglass cloth "carrier" containing the adhesive between the adherends at the areas to be bonded, and place the assembly into a press or autoclave. The force is applied to the specimen faces by the application of hydraulic pressure in the laboratory press or pneumatic pressure in the autoclave. The heat needed to cure the adhesive is applied from the outside of the specimens, via the heated

platens in the press or the heated atmosphere in the autoclave and through the adherends, to the adhesive between them.

The metal platens of the press have considerable thermal mass, thus limiting the rate of heatup and cooldown of the entire assembly. Similarly, autoclave heating/cooling rates often have considerable limitations. Manual or programmed platen power controls are used to set the bond temperature history within the heating/cooling rates possible. Recorders and/or indicators monitor bonding load and temperature histories.

The specimen assembly is subjected to a controlled history of time, temperature and pressure to cure the adhesive. Pressures of 50 to 100 psi and temperatures to 350°F for epoxies and 650°F for polyimide adhesives over a period of several hours are typical. If the part or specimen is subsequently found (through nondestructive evaluation procedures) to be poorly bonded or misaligned, it is very difficult (if at all possible) to correct and much costly effort is usually wasted. Of course, the adherend materials must be able to accept the temperature/pressure bonding history without degradation, or the adhesive cannot be used.

Thermoplastic adhesives are available commercially which can be used to bond composite or metallic parts and specimens. However those thermoplastic adhesives which can be processed at moderate temperatures do not have adequate thermal or solvent resistance for aerospace structural applications. The thermoplastic adhesives which might be stable enough require high processing temperatures which could severely damage polymer matrix composites if subjected to the relatively long processing times of presses or autoclaves. Thermoplastic adhesives and some thermosetting adhesives do

not inherently require long processing times - a few minutes to heat the thermoplastic to achieve a viscosity low enough to obtain flow and wetting of the adherend surfaces (plus a short time for cure for the thermosets) is sufficient. However, the current heated platen press or autoclave equipment limits the temperature/time conditions possible for bonding.

Some research and development of adhesive bonding processes using induction heating have been reported in the literature. An example is the commercially available EMA process (refs. 2 and 5) which uses powdered susceptor materials to concentrate the heating effect in the bond. This process utilizes induction frequencies of 3 to 30 MHz for optimal "coupling" with the susceptor powders. However, such high frequencies may severely limit the depth of penetration of the induction heating field; the power of that field must penetrate through the adherend to heat the adhesive bond line effectively.

Recognizing the man-hour and other economic factor improvements that are achievable if adhesive bonding processes for typical aerospace component geometries could be accomplished in minutes, a multidisciplinary team at the Langley Research Center (LaRC) has developed concepts to bond a variety of materials and geometries, using advanced induction heating technology. In general, the objectives of this research are to conceive rapid, energy efficient, reliable adhesive bonding techniques for high performance aerospace materials and to develop prototype equipment for specimen bonding, panel bonding, or simple component bonding, and field repair of structures. These concepts are designated herein as Rapid Adhesive Bonding (RAB) concepts.

TARGET CRITERIA

At the inception of this program, the LaRC Rapid Adhesive Bonding Concepts Team set specific target criteria for rapid adhesive bond strength and bonding conditions. These criteria are listed in figures 1a and 1b as a series of "needs" and "wants". If a given concept could not meet a "need", that concept was rejected and alternate concepts developed until the "need" was met. Given the current status of adhesive bonding and the desire for portable, energy efficient procedures, the "wants" criteria indicate a performance that would be a definite improvement in the state-of-the-art.

The mechanical property criteria (fig. 1a) were developed for the ASTM standard overlap shear specimen tests, D1002 and D3163. Metallic adherends (e.g. titanium or aluminum alloy) permit the development of full cohesive strengths of the adhesive in these tests. Fiber reinforced adherends, on the other hand, typically delaminate at shear stresses around 2000 psi at room temperature and 1500 psi at their maximum operating temperatures. The criteria were selected in recognition of the properties of commercial low- and high-temperature adhesives in these tests. In determining the strength of bonds in panels or other assemblies, it was assumed that "witness" overlap shear specimens would be cut from panels bonded with the assembly.

The bonding condition criteria are listed in figure 1b, in terms of bond times, or bonding rates, bonding pressures, adherend and bond dimensions, and power requirements. Also listed in figure 1b are needs and wants for monitoring. The goal is to have a process so "forgiving" that bond temperature, for example, need not be maintained more accurately than

± 20°F of the nominal temperature, with minimal effect on bond quality. Processes or adhesives that require closer control than ± 10°F were considered unacceptable. Similar criteria are listed for power control and bonding pressure control.

SPECIMEN BONDING

Equipment and Procedure

Bonding Equipment - An overall view of the rapid adhesive bonding equipment for overlap shear specimens is shown in figure 2. Much of the equipment is identical to that used for conventional bonding including the load cell, the temperature and load indicators, and the laboratory press. In the latter, the conventional heated platens have been replaced by a toroid induction heater with its power controller. The specimen assembly is located in a specimen fixture for ease of alignment. The power and frequency indicators are optional and were used only during the equipment development phase of this research.

The toroid induction heater used in this equipment is shown in figure 2. Its development is detailed in a U.S. Patent application*. In this application, bonding pressure is applied through the toroid, necessitating detailed changes in geometry, to be discussed subsequently. The toroid geometry, winding pattern, and power supply are designed to form a circuit operating at 30 to 100 KHz, which will be "self-tuning" to the geometry/physical properties of the joint being bonded. Using such frequencies, in conjunction with thin screen or perforated foil metallic susceptors, RAB

*NASA Case No. LAR 12540-1

equipment has good induction field penetration of the adherend. Achievement of very rapid susceptor heating rates (e.g. 600 to 1200°F/min) is possible with low power input.

An example of the type of heating susceptor used for specimen bonding is a commercial steel screen, shown in figure 3. In specific cases of data noted in the following the screen was flattened in a machine press to about 0.008-inch-thickness. It was then impregnated with a thermoplastic adhesive such as Union Carbide's UDEL P1700 polysulfone by heating between platens of a standard laboratory press until the adhesive had melted into the screen. The adhesive/susceptor is typically 0.020 to 0.025-inch-thick when ready for RAB. Other materials, such as perforated stainless steel foils with combinations of high resistance and low reluctance can be used as susceptors. Type 410 stainless steel foil, 0.005-inch thick, has been used with good results as an inexpensive corrosion resistant susceptor, sandwiched between layers of thermosetting adhesive film or scrim cloth.

The components of an overlap shear specimen which conforms to ASTM D1002 or D3163 are shown in figure 4. In this example the adherends are 0.05-inch-thick titanium alloy, but similar adherends of aluminum alloy and high strength fiber reinforced polymeric composites have also been bonded, with excellent results (described subsequently). The flattened steel screen susceptor impregnated with the thermoplastic adhesive is the other component of the specimen.

A special fixture was devised to align the specimen components prior to bonding. The fixture is shown in figure 5. It may be machined from any nonconducting material. In this case the base was machined from bakelite, with cutouts and location screws for the adherends. In the bonding region

the cutout is deeper and fibrous ceramic insulation topped by a Kapton® film was used under the specimen when P1700 polysulfone adhesive (ref. 6) was the bonding agent. Another layer of Kapton, topped by fibrous insulation is placed atop the specimen to prevent heat conduction losses and to avoid bonding of specimen flashing to the toroid head. This fixture and the materials used in it functioned well for bonding temperatures to at least 850°F, since the heat is concentrated in the specimen bond lines and the bonding times are relatively short.

Bonding Procedure - Bonding is accomplished by assembling the specimen in the specimen fixture, placing the fixture in the press under the toroid head, and applying pressure and the induction field.

The assembled specimen in the fixture (figure 6) was placed under the toroid induction heater in the press as shown in figures 7 and 2. In order to apply bonding pressure to the specimen uniformly through the toroid, a flat area was machined and a filler piece of nonconducting ceramic material such as glass was cemented in the toroid gap (fig. 7). Application of uniform pressures to at least 200 psi on the specimen overlap was readily accomplished with this configuration.

When the specimen fixture was in place, the bonding pressure was applied with the hydraulic press. The toroid induction heater was energized. In the specific cases described herein, 300 watts or less of 120 volt, 60 Hz power were input to the toroid circuit. The self-tuning capability of the toroid circuit tuned the entire assembly to about 50,000 hz for the specimens bonded. With polymeric composite adherends, this power

®DuPont's registered tradename for their polyimide film.

was concentrated as heat almost entirely within the steel screen or foil susceptor, thus concentrating the heat within the bond line and minimizing detrimental thermal effects on the adherends. In the titanium specimens, both the steel screen susceptor and the adherends absorbed electromagnetic energy and bonding temperatures up to 800°F were always reached within one minute and usually in 1/2 to 3/4 minute. The prescribed bonding temperature was maintained for the prescribed time to promote further wetting of the adherend surface by the adhesive, using the simple input voltage controller shown in figure 2. When the bond time was completed, the power was cut off and the specimen cooled to a temperature below the solidification temperature of the adhesive, which occurred within several minutes. At this point, the pressure was released and the bond was completed. Titanium alloy specimens are shown as-bonded and after shear testing in figure 8. The entire process, from specimen layup through removal from the fixture, was usually completed within 15 minutes. These concepts provide a more rapid, more controllable, and more energy conserving process then conventional press bonding with heated platens or autoclave bonding of specimens.

Adherends, Adhesives, and Bond Strengths

Titanium Adherends - Table I and fig. 10 show overlap shear strengths (per ASTM D1002) of Ti-6Al-4V titanium alloy adherends (0.05-inch-thick), fabricated by RAB using P1700 polysulfone thermoplastic adhesive and the 0.008-inch-thick flattened steel screen as a susceptor in nearly all cases. Data are shown for both primed and unprimed adherends, bonded at temperatures from 400°F to 800°F. All specimens were bonded at 80 psi. Hold time under pressure at the bond temperature was varied from 1/4 to 5 minutes. All shear data are from room temperature tests except for

specimens IB 32-1 and IB 32-3 which were tested at 300°F. Two failure modes were noted on inspection of these specimens after the shear test: cohesive failure in the thermoplastic adhesive and adhesive failure on the adherend surface. Some specimens exhibited a mixed mode of failure with both of these mechanisms occurring (see figure 9).

In general, higher bonding temperatures resulted in better wetting of the titanium adherend surface by the P1700 adhesive, promoting better bonding as indicated by totally cohesive failures and overlap shear strengths from about 3000 psi to more than 4500 psi at room temperature. These strengths compare favorably with bond strengths quoted by the adhesive supplier in his product literature for autoclave or press bonding. These results were achieved at bond temperatures from 650 to 800°F with 2-minute holds for the primed specimens and at bond temperatures from 700 to 800°F with 2-minute holds for the unprimed specimens. Longer hold times at any bonding temperature promoted better bonding (as indicated by both increased percentages of cohesive failure and increased shear strengths). No P1700 adhesive degradation during the bonding was noted until the bonding temperature exceeded 800°F. Bonds made at both 825 and 850°F exhibited some degree of adhesive degradation.

Graphite/Polyimide Adherends - Table II shows similar data for graphite fiber reinforced LARC-160 polyimide composite adherends (ref. 7), again bonded with the P1700 thermoplastic polysulfone adhesive impregnated into the flattened steel screen susceptor. In order to emphasize the simplicity of the RAB process, no priming was used on the specimens prior to bonding. The surfaces were simply wiped with a suitable solvent. It is expected that priming of the specimens would result in adequate bonds at lower temperatures than those needed for unprimed adherends.

In all cases in Table II, the specimens were heated under 80 psi bond pressure to bonding temperature within 1 minute and held at bond pressure for 2 minutes or 5 minutes, then cooled rapidly and removed from the press for shear tests at room temperature. In typical shear tests of this kind, 3 modes of failure are often noted: cohesive failure in the adhesive, adhesive failure on the adherend surface, and delamination of the outer plies of the adherend. The adherends used for this evaluation were of high quality and no delamination of the adherends was noted in any of these tests.

Higher bonding temperatures and longer bonding times generally resulted in better wetting of the graphite/polyimide adherend. For the bonds made at 750°F for 5 minutes and at 800°F for 2 minutes or 5 minutes, strengths above 2500 psi were measured. Bonds made at 700°F and at 750°F for 2 minutes showed inadequate wetting of the adherend surface by the adhesive, as indicated by the failure surface character. Perhaps most importantly, this data indicates that bonds can be made using RAB at temperatures which would probably degrade polyimide matrix composites in standard press or autoclave bonding processes, because of the temperature/time histories involved. The relatively short time and localized heating utilized in RAB precluded Gr/LARC-160 adherend degradation, as indicated by the complete absence of adherend delamination in the tests noted in Table II, with one specimen achieving a shear strength of 3900 psi.

Graphite/Epoxy Adherends - The applicability of this process for bonding polymeric matrix composites with thermosetting adhesives is indicated by the data in Table III. Graphite fiber reinforced epoxy adherends were bonded as follows: the adherend surfaces were wiped with a

suitable solvent. The bond was formed using a layer of American Cyanamids HT-424 epoxy-phenolic adhesive (ref. 8) on a fiberglass cloth carrier atop and below the flattened steel susceptor screen, all sandwiched between the adherends. Again, the adherends were not primed. This procedure resulted in relatively thick bond lines in the specimens but good room temperature overlap shear strengths were attained, with all specimens but one exhibiting cohesive failures.

With this combination of adhesive and adherends a relatively wide variation of bonding conditions - temperature, time, and pressure - were found to have little effect on bond strengths. Temperature/time combinations from 400°F/5 minutes to 450°F/2 or 5 minutes resulted in good bonds. Perhaps of most interest in the data of Table III is the finding that bond pressures as low as 5 psi and as high as 80 psi produce good bonds (figure 11), with 10 to 20 psi at 450°F producing the bonds with highest room temperature strengths. Again, no adherend degradation was detected for the highest temperature/longest time RAB bonding conditions.

Adherends of Unlike Materials - The versatility of the rapid bonding concepts was again demonstrated by utilizing the process described in the preceding paragraphs to bond unprimed titanium alloy to unprimed aluminum alloy sheet with the HT-424 adhesive, at temperatures from 350 to 450°F and bonding times of 2 or 5 minutes. The data are shown in Table IV. With one exception, all bonds exhibited ASTM D1002 overlap shear strengths higher than 3000 psi, again indicating the remarkable insensitivity of strength to bonding parameters. Two specimens (IB51-1 and -2) were postcured, freestanding, in an oven at 350°F for 1 hour. Bond strengths were increased to about 3600 psi by this postcure. Hardness surveys on the aluminum

adherends before and after bonding showed no differences. Thus, minimal effects on mechanical properties of the aluminum by the RAB conditions are expected. The implications for bonding of components by spot bonding to "self-fixture" the component, followed by a freestanding postcure to complete the thermosetting adhesive bond, appear obvious.

Comparison with Press Bonding Data - The rapid bonding process was directly compared with laboratory press/heated platen bonding of titanium alloy adherends using an experimental thermoplastic adhesive, BDSDA/APB ref. 9) which was formulated to have good flow conditions while retaining good elevated temperature properties. The data are shown in Table V and figure 12. Two press conditions were used. In the first condition the specimens were placed between cold platens and a conventional heating rate of 9°F per minute to a 600°F bond temperature was achieved. Bonding was completed by holding at 600°F and 300 psi for 15 minutes followed by slow cooling (limited by the platens). The total time for this procedure was about 2.5 hours. In the second press condition the specimen assemblies were placed between preheated platens so that heatup rate was considerably faster, with all other conditions remaining the same. This cut total press bonding time by 50 minutes. The specimens bonded with the new process were made by a process slightly different than that described in the previous paragraphs. The specimens were laid up similarly to those used in the press bonding and the flattened steel screen susceptors were placed under the specimens to heat to bonding temperatures through the bottom titanium adherend as well as the self heating of the titanium adherends. These specimens were heated to the 572°F bonding temperature in 5.3 minutes, under 100 psi pressure, immediately cooled to room temperature under pressure and

the susceptor, which was not bonded to the specimen, was discarded after pressure was released.

Table V shows that average ASTM D1002 overlap shear strengths of the press bonds was slightly increased by increasing the heating rate in the bonding process. However, the strengths of the rapid bonds (made at lower temperature, lower pressure, and much shorter times than the press bonds) were significantly higher than those obtained with either of the press bonding procedures.

Adhesives Applicable to RAB

Table VI lists the adhesives investigated which responded to rapid adhesive bonding to produce strong bonds (R. T. lap shear strengths above 3000 psi for metallic adherends, above 2000 psi for composite adherends). When the adhesive screening phase of the RAB team's efforts began, there was little expectation that many thermosetting adhesives could be used for rapid bonding because the crosslinking mechanism was expected to require significant cure time. It was therefore a pleasant surprise when all but two of the thermosetting adhesives screened (FM 73 and FM 300, ref. 90) were found to produce strong bonds in several minutes with the rapid bonding equipment. The temperatures used for the rapid bonding were somewhat higher than those used for press or autoclave bonding, but no thermal deterioration of the adhesive occurred, because of the short times involved. Cure (crosslinking) was rapid during the RAB conditions. Post cure investigations showed only small increases (if any) in R. T. lap shear strength of any of the adherend/thermosetting adhesive combinations investigated. An example of the screening data is shown for two thermosetting adhesives, AF-163 and EC-1386 (refs. 11 and 12), in Tables VII and VIII.

Thermoplastic adhesives were expected to respond well to rapid adhesive bonding, because melting of the adhesive, wetting of the adherend surface, and cooling below Tg should be all that is required to make bonds in these adhesive systems. This was found to be the case; all thermoplastic adhesive investigated (Table VI), performed well once bonding conditions (temperature, pressure, heating rate) were developed with consideration of the idiosyncrasies of the specific adhesive (e.g. - pressures above 100 psi must be used with some polyimide adhesives to prevent foaming). In some cases the fast heating rates (600 to 1200°F/minute) seemed advantageous to development of good adhesive flow during the "wetting phase". A small amount of residual solvent in the thermoplastic prior to bonding could promote flow and wetting. That residual solvent is probably present when the melt temperature is reached during RAB. The relatively slow heat up rates of press bonding or autoclave bonding would enable this solvent to escape before melt temperature is reached. Once melt and flow have taken place in RAB, the residual solvent will readily escape from the bond line, leaving no solvent to degrade the environmental performance of the adhesive bond.

Environmental Exposures - The use of steel screen or stainless steel foil susceptors in the adhesive bond line precipitates questions regarding the environmental stability of such bonds due to adherend/adhesive/susceptor thermal expansion mismatch, dissimilar material (electrolytic cell) corrosion, etc. The thermal expansion mismatch concern was investigated by thermally cycling titanium alloy adhesives rapidly bonded with LARC-TPI (ref. 13) adhesive from -100°F to +450°F and thermally cycling T300/5208 Graphite/Epoxy adherends bonded with HT-424 epoxy-phenolic adhesive from

-100°F to +180°F. Eight specimens of each material combination (with steel screen susceptors in the bond lines) were subjected to 1000 thermal cycles, then tested for residual lap shear strength at room and elevated temperature and the data components compared to control specimens (no thermal cycling). The results showed no degradation in average lap shear strength due to the thermal cycling and no increase of coefficient of variability in the data, compared to the control specimens and compared to similar specimens (without susceptors) bonded by standard press techniques.

Other titanium alloy specimens and graphite/epoxy overlap shear specimens were rapidly bonded using both thermosetting and thermoplastic adhesives, then subjected to 72-hour exposures in boiling tap water and subjected to lap shear tests at both room temperature and elevated temperature. In some cases, severe losses in lap shear strength were noted, but in no case was the strength degradation worse than that measured for press bonded specimens with no susceptor or that quoted in the literature supplied by the adhesive manufacturer. While these results of short-time environmental exposure evaluations do not conclusively prove that long term exposures will not affect bond strength, they are encouraging. Further details on environmental exposures are presented in the following sections.

PANEL AND COMPONENT BONDING

Bonding Equipment

An overall view of the Rapid Adhesive Bonding (RAB) equipment for overlap panel assemblies is shown in figure 13. The toroid induction heaters are mounted with a load cell on a support structure, which in turn is mounted to a transverse alignment slide. That slide is located on a

longitudinal traversing carriage, which travels along a standard machine bed. The power supply and controller and load indications are on the transverse slide, while thermocouple and infrared sensor monitors of panel specimen temperature are on the bed. The panels to be bonded, 2 feet long in this figure, are located in a simple insulated panel support. This equipment is detailed in the following paragraphs.

<u>Toroid Heater, Power Supply, and Susceptors</u> - The toroid induction heaters used in the RAB equipment were described previously.* Several other geometries were investigated but none provided improvements in heating efficiency or uniformity. In this case, two toroids are shown in tandem (figs. 13-15) on the toroid support. The finding that such a mounting is possible without undesirable interactions of the electromagnetic fields of the toroids allows the bonding area to be enlarged; thus, when used in an overlap bonding application, bonding head speeds can be substantially increased through the use of additional multiple tandem heads. Teflon boots were mounted on the bases of the toroids to enable them to slide smoothly across the surface of the parts to be bonded. The power supply shown (which uses approximately 300 watts or less at 60 Hz and 120V for each toroid) provides the required circuitry for a self-tuning inducting-heating circuit which operates at 30,000 to 100,000 Hz. Susceptors concentrate the induction heating effect in the bond line. The most successful of these developed for this application are the flattened steel screen and a perforated stainless steel foil described previously.

<u>Monitoring Instrumentation</u> - The monitoring instrumentation is used to maintain selected levels of bonding pressure and temperature. Bonding pressure is applied through the toroid head via the loading spring (figs. 14

*See NASA Invention Disclosure, Case No. LAR 12540-1

and 15), controlled by the manual control adjustment (fig. 13) and monitored by the load cell and its readout display (fig. 14). Although it was initially expected that a feedback load control would be necessary to maintain constant load (contact bonding pressure) during the bonding process, it was found that a simple manual control easily maintained pressure within 1 psi during panel bonding.

Temperature monitoring in the adhesive bond line is considered to be an important requirement of this RAB process, because the heating is concentrated in the bond line in all applications in which a susceptor is used. A commercially available fiber optic infrared temperature probe (fig. 16) which can monitor a very small region of the bond line from the edge of the bond was used with a special alignment fixture to provide the required feedback signal; it was calibrated against a thermocouple in the bond line of a test specimen of each of the materials to be bonded. An alternative temperature monitoring scheme which was also found applicable was to use a spring-loaded thermocouple probe in the molten adhesive flashing, tracking with the toroid head(s) as they pass over the panel.

Machine Bed and Related Hardware - A standard machine bed is used as a support for the RAB equipment. As shown in figure 13, this bed has a longitudinal traversing carriage which can automatically move at controlled rates of speed. Attached to the carriage is a manually operated transverse alignment slide (figures 13 and 14). An aluminum alloy fixture was designed to hold multiple toroids, the loading spring, and a load cell, and a manual load adjustment handle (figures 13-15). This fixture also supports the fiber optic infrared temperature probe and the infrared temperature sensor.

Panel Specimens and Specimen Fixture - Overlap bonded panels are shown in figures 17-20. These panels were made by placing one sheet of either titanium or graphite/epoxy on the panel support atop several layers of fibrous insulation. The panels were cleaned by simple degreasing and grit blasting. Neither the Gr/Ep or titanium sheet were primed before bonding. A 3/4-inch wide strip of adhesive tape the length of the panel was laid on this sheet with 1/8-inch protruding along the edge. If a susceptor was used it was placed over the adhesive and another strip of adhesive tape placed on it. The other sheet of titanium or graphite/epoxy was then laid on this assembly to produce a 1/2-inch overlap, the length of the sheets. As shown in figure 17, the specimen clamps were then fastened. The clamps along the panel were "snugged" so that the panel could slide on them as it thermally expanded during bonding, so that thermal distortions would be minimized.

Bonding Procedure

The bonding procedure consists of installing the parts to be bonded in the fixture, positioning the toroid heads over a dummy "on-ramp" specimen of the same material and geometry as the work, bringing the dummy specimen (with a thermocouple in the bond line) to the bonding temperature, and initiating a traversing carriage movement at the required rate. Manual corrections for temperature and bonding load are readily made by adjusting the power and/or load controllers. These functions can be readily automated. When the work has been traversed by the toroids they are brought to a stop on an "off ramp". Specific details of thin sheet overlap panel bonding follow.

Panel Insertion - The components of the panel, thin sheets or plates up to at least 1/4-inch thick of metallic (e.g. titanium) or composite (e.g.

graphite fiber reinforced epoxy) adherends as long as 5 feet or more with adhesive tapes and (if required) susceptors are mounted in the fixture as described previously.

Overlap Panel Bonding - As shown in figure 17, an "on ramp" of the same graphite/epoxy material and geometry is located so that the toroid(s) can be located on it and bonding pressures and temperatures preset. The traversing mechanism is engaged and the toroid heads slide from the on-ramp to the panel and begin melting and curing the adhesive as the toroids progress along the panel. In figure 17 the toroids, moving at 0.5 inch per minute and applying a bonding pressure of 20 psi, have just completed movement onto the panel. In figure 18 they are moving along the panel, melting and curing the HT 424 epoxy-phenolic thermosetting adhesive under the toroids as they pass while maintaining a bond temperature of 450°F. Similar procedures are used for metal adherend overlap panels (e.g. - titanium sheets with LARC-TPI thermoplastic adhesive at 650°F).

Bonded Panels

Titanium alloy (Ti-6Al-4V) panels are shown in figure 19. Panels were made with the steel screen or perforated stainless steel foil susceptor in the bond line (so that the heating was concentrated in the bond line) or without a susceptor (by heating the adherends in the induction field). Graphite/epoxy panels bonded with the HT 424 adhesive are shown in figure 20. Again they were made with and without susceptors. An important finding in this application of RAB is that graphite epoxy laminates can be heated directly in the induction field of the toroid heaters. As figures 19 and 20 indicate, distortion in these panels was not excessive, considering that unstiffened sheets were bonded. The distortion was on the same order as that seen in similar panels bonded in a press or autoclave. The panel

bonds were evaluated by nondestructive C-scan ultrasonic techniques, photographed, and then machined into 1-inch wide strips which were then subjected to the standard ASTM D1002 or D3163 overlap shear tests in either the as-bonded condition or after environmental exposure.

Bond Strengths

Graphite/Epoxy Panels - Some lap shear specimens cut from a graphite/epoxy panel bonded with HT 424 epoxy-phenolic adhesive and with the steel screen susceptor were tested at room temperature (RT) and at 180°F as-bonded, at RT and 180°F after 1000 thermal cycles from -100 to +180°F, and at RT and 180°F after a 72-hour boiling water exposure, in accordance with ASTM D1002 or D3163. Four as-bonded specimens averaged 3940 psi lap shear strength (LSS) at RT and two specimens averaged 3200 psi at 180°F (compared to 2950 psi at RT and 2970 psi at 180°F for similar specimens fabricated by standard press bonding). After thermal cycling the RAB specimens averaged 3640 psi LSS at RT and 3200 psi at 180°F (compared to 2970 psi at RT and 3140 at 180°F for similar specimens fabricated by standard press bonding and thermally cycled). Thus, the RAB process has no degrading effect on shear strength of Gr/Ep//HT-424//Gr/Ep bonds, compared to standard bonding, and thermal cycling does not significantly degrade these properties. The water boil exposure degraded bond strengths about 35% at room temperature and 28% at 180°F. This degradation is approximately the same as that noted for the HT 424 adhesive in the adhesive supplier's literature (ref. 8).

A second Gr/Ep//HT-424//Gr/Ep panel with the steel screen susceptor (fig. 20) had somewhat lower lap shear strengths than those noted above when the strips machined from this panel were tested: at RT four specimens

averaged 3390 psi LSS and, at 180°F, two specimens averaged 2750 psi. This variation in strength is not surprising, as failures in composite LSS panels are often dependent on delamination of the adherends due to the peeling action in the test. Strengths above 3000 psi at RT and above 2000 psi at elevated temperature are considered very good with graphite/epoxy adherends. Within a given panel, worst case strength variability (maximum LSS - minimum LSS) was 8 percent of the mean at room temperature and 16 percent at 180°F. In composite and adhesive testing, these are not high variabilities.

The Gr/Ep//HT-424//Gr/Ep panel bonded with no susceptor had somewhat lower LSS than those noted above for the panels bonded using the susceptor. Four RT LSS specimens averaged 2090 psi and 2 specimens averaged 1910 psi at 180°F. The data variability for these specimens was considerably higher than that noted previously for the panels bonded with the susceptor. However, these strengths are respectable for composite adherend lap shear specimens.

Titanium/Aluminum Panels - Titanium sheet was bonded to aluminum sheet using the HT 424 epoxy-phenolic thermosetting adhesive and the steel screen susceptor. The panel was machined into lap shear specimens and tested according to ASTM D1002. Average room temperature lap shear strength for 8 specimens was 3160 psi. LSS variability was 7 percent. These values are considered to indicate that RAB is a widely applicable bonding process, since neither the titanium (Ti-6Al-4V) or the aluminum (2024-T3) alloy adherend sheets were primed before bonding, the bonding pressure was 40 psi at a bonding temperature of 450°F, and the bonding speed was 0.5 inch/minute (each region in the bond was heated to 450°F for 2 minutes).

Other Geometries - Panels or structures of many geometries can be bonded by the RAB process. Examples are stiffeners or stringers on panels (figure 21), repair patches, etc. Simple fixtures would have to be designed to hold the specific geometries in place. The only significant geometric limitation would be that one of the adherends must be 1/4 inch or less in thickness and the toroids must traverse and apply pressure to the outer surface of the adherend.

Honeycomb-core panels (figure 22) have also been bonded using rapid adhesive bonding. Titanium or aluminum sheet to titanium or aluminum core bonds are possible. Composite face sheets can readily be bonded to an aluminum or nomex honeycomb core. The bonding can be done one surface at a time, allowing for examination of the first bond (by observing through the honeycomb) before the second bond is made on the other surface; the relatively short time required for bonding alleviates the prohibitive cost of bonding one surface at a time in a press or autoclave process.

The use of the steel screen or stainless steel susceptor in the bond line of polymeric composite face sheet honeycomb core panels or stiffened panels may provide an additional advantage for aerospace applications-lightning strike protection. Lightning protection in bonded regions can be provided with a negligible structural weight penalty if RAB is used.

In a very complex structure, where autoclaving or press bonding with shaped platens is advantageous, RAB may still have an important role. RAB can be used in a "spot bonding" mode to hold parts in place before they are inserted into the autoclave or press, thus alleviating the need for a good deal of expensive fixturing. The spot bonding part is already "self

fixtured" as it enters the autoclave or press wherein the bonding is completed for continuous coverage.

FIELD REPAIR

Current Status

Field repair is the most challenging area of aircraft maintenance. The requirements for repair integrity and quality are difficult to meet because of the constraints of field operations. Bolted or riveted metallic panels are currently the most commonly used methods for structural field repairs in the aerospace industry (refs. 14-16). Such repairs require simple, readily available equipment and are usually easy to accomplish. However bolted or riveted repairs usually encompass areas much larger than the original damage, are heavy, and may have long-term durability problems.

A typical bolted titanium plate repair in a structural panel of graphite fiber reinforced epoxy material is shown in figure 23. Such bolted repairs in high performance composite structures must be very carefully designed and attached because of the difficulty of transferring high loads at discrete locations in a relatively brittle material (compared to conventional metallic structures). In the figure, 42 bolts are used to avoid unacceptable stress concentrations. Adhesively bonded field repairs are currently sparcely used, usually in lightly loaded secondary structure aircraft applications (refs. 14-17). Some exploratory research is addressing adhesively bonded repairs in more highly loaded structures (refs. 17-19). Factors which have limited wider use of adhesively bonded repairs include complex and bulky equipment such as heating blankets and

fixtures, storage environment sensitive adhesives, and quality control uncertainties.

Requirements

Field repairs must be executed in the shortest possible time with simple, lightweight equipment and low power requirements (ref. 16). In the case of military aircraft in a combat zone, if repairs require more than 24 hours, the aircraft may simply be discarded and "cannibalized" for parts. The equipment must be rugged, easily transportable, versatile, and easy to use. Field repair strength recovery targets are often 80% to 100% of the undamaged structural strength with thermal stability requirements from -65°F to 250°F (ref. 16). Repair in the field must be possible under severe weather conditions in primitive shelters. Repair materials must remain stable and handleable at temperatures from below 32°F to 120°F. All of these requirements must be satisfied at a reasonable cost.

RAB for Field Repair

The Rapid Adhesive Bonding Concepts described previously have been further developed to meet the above requirements. The induction-heating power supply has been engineered into a "ruggidized", solid-state electronics unit, in a one-cubic-foot package weighing 20 pounds. A hand-held bonding gun weighing 3 pounds plugs into this power supply on a long power cord. The maximum power required for the single-toroid head is 300 watts. Adhesive bonds are attained rapidly by directly heating the adhesive in the bond line (through the susceptor) with minimal heating of the structure surrounding the bond line. Lightly loaded or "cosmetic" repair bonds can be made in several minutes at an average power input of 150

watts on metallic, polymeric, or polymeric matrix composite secondary structures. Typical examples follow.

Windscreen Repair - The repair of a helicopter windscreen in the field is currently achieved by "stop-drilling" the cracks emanating from the damage region. An acrylic or polycarbonate patch is drilled with matching holes and "laced" to the damaged windscreen with safety wire. This patch does not seal out the environment during operations. Figure 24 illustrates the potential for RAB field repair of such a windscreen. Several "damage holes" were made in a polycarbonate windscreen with a .45 caliber service pistol to simulate battle field damage. The polycarbonate patch and a ring of steel susceptor screen were cut from stock and laid over the holes. The hand held induction head applied the required pressure while heating the screen to the melt temperature of the polycarbonate. The head was moved around the circumference of the patch to complete the bond in less than 10 minutes per hole. The patches formed doubler plates over the cracks emanating from the bullet holes to restrain crack propagation. The bonded patches (figure 25) should be effective in sealing the helicopter interior from rain and dust during operations. The Rapid Adhesive Bonding field repair technique provides a faster, simpler, stronger repair than the conventional field repair technique.

Hydraulic Line Repairs - Another potential application for RAB is field repair of hydraulic fluid and fuel lines. Current fluid line repair procedures often utilize shrink sleeves (fabricated from alloys such as Nitinol, Tinel®, and Betalloy® alloys and an adhesive, ref. 20). An open

®Registered Tradename of Raychem Corp.

flame from a torch is often used to heat the sleeves to the temperature at which they shrink (415°F) and bond to the line, effecting the repair. In the confined spaces of an airframe, fuel or hydraulic line vapors from the damaged line are often present; any open flame procedure can be hazardous. Furthermore, the uneven heating of a torching procedure can overheat the fittings. Oxidation, adhesive damage, uneven shrinkage, and warpage of the fluid line can result.

Induction heating, using the RAB process was investigated as a simple method to heat the shrink sleeve fittings more uniformly and far more safely than a torch process (figure 26). The results of these investigations are very promising. The RAB process heated the fittings uniformly, and rapidly with minimal effect on surrounding areas. The hydraulic line repaired by RAB, figure 27, was tested to more than twice its rated operating pressure with no leakage. Repair of fluid lines in aerospace structures appears to be a very promising application for RAB.

<u>Surface Repairs</u> - A common aircraft supportability requirement is the repair of small surface defects such as dents and gouges caused by impacts from runway debris, minor bumps, inadvertent occurrences during repair, etc. These are not structural concerns, but must be repaired to maintain surface integrity and, in many cases, aerodynamic smoothness. Rapid Adhesive Bonding techniques can be used to repair such minor defects. A patch of metallic or composite material, susceptor, and adhesive can be readily prepared with simple hand tools to fit the required repair geometry. A short bonding cycle using the hand held unit shown in figures 24 and 26 is usually all that is required to wet the surfaces and cure the adhesive into a bond with adequate strength. The repaired surface can then

be smoothed, if necessary, with conventional tools for this purpose. Such patches on a graphite/epoxy composite panel surface are shown in figure 28.

CONCLUSIONS

Rapid Adhesive Bonding (RAB) concepts have been developed at the NASA Langley Research Center. RAB utilizes induction heating methodology to provide heat directly to the bond line and/or adherend without heating the entire structure, supports, and fixtures of a bonding assembly. Bonding times for standard ASTM overlap shear specimens can be cut by a factor of 10 to 100 compared to standard press or autoclave bonding. High lap shear strengths can be generated with a range of adherend materials (including metals and polymer matrix composites) and adhesives (both thermoplastic and thermosetting). Short term thermal cycling and water boil exposures have shown encouraging environmental stability for these rapid bonds, including those which contain steel screen or stainless steel foil susceptors in the bond lines.

The RAB concepts were extended to continuous seam bonding of metallic and composite panels with promising results for bonding of both like and unlike adherends. Rapid bonding of other geometries such as face sheets of fiber-reinforced polymeric matrix composites or titanium alloy to titanium honeycomb core were proven feasible.

The inherent portability of RAB equipment suggested that field repair procedures for adhesive bonding of damaged metallic, polymeric, or composite structures are possible. Initial development of these procedures showed that field bonding of patches of titanium alloy and graphite/epoxy composite

materials could be bonded to typical aircraft panels. Furthermore, variations of the RAB process can be used to repair polycarbonate or acrylic windscreen materials and hydraulic tubing.

The promise of advanced composite and bonded metallic structures for improvements in structural efficiency and cost is limited by current processing and repair technology. Rapid Adhesive Bonding Concepts show promise for significant technology advances.

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TABLE I - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED TITANIUM

Ti-6Al-4V Titanium Alloy Adherends, P1700 Polysulfone Adhesive

Specimen Number	Primed Speci-men	Susceptor Material/ Thickness, inch	Bonding Temperat-ure, °F	Hold Time at Bond Temp., min.	Bond Pres-sure, psi	Shear Test Temp., °F	Bond Line Thick-ness inch	Percent Cohesive Failure (a)	Overlap Shear Strength, psi	Remarks
IB29- 1	Yes	Steel Screen/ 0.008	700	2	80	75	0.010	100	4020	
IB29- 2	Yes	"	700	2	80	75	0.010	100	3680	
IB30- 1	Yes		650	2	80	75	0.012	100	3500	Alinement fixture not used
IB30- 2	Yes	"	650	2	80	75	0.012	95	3850	
IB30- 3	Yes	"	400	2	80	75	--	0	0	No adhesion
IB30- 4	Yes	"	450	2	80	75	0.038	0	1200	
IB30- 5	Yes	"	500	2	80	75	0.025	5	3240	
IB30- 6	Yes	"	500	2	80	75	0.022	0	1530	
IB30- 7	Yes	"	550	2	80	75	0.013	50	2775	
IB30- 8	Yes	"	550	2	80	75	0.020	0	1925	
IB30- 9	Yes	"	600	2	80	75	0.018	90	2900	
IB30-10	Yes	"	600	2	80	75	0.013	90	2900	
IB30-11	Yes	"	700	2	80	75	0.010	100	3195	Susceptor Screen Not Well Aligned
IB30-12	Yes	"	700	2	80	75	0.008	100	3775	
IB30-13	Yes	"	750	2	80	75	0.009	100	4300	
IB30-14	Yes	"	750	2	80	75	0.009	100	3585	
IB30-15	Yes	"	800	2	80	75	0.010	100	3820	
IB30-16	Yes	"	800	2	80	75	0.009	100	3830	
IB32- 1	Yes	"	700	2	80	300	0.009	100	3145	
IB32- 3	Yes	"	700	2	80	300	0.008	100	3190	

(a) Cohesive failure in thermoplastic adhesive; balance is adhesive failure on adherend

TABLE I - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED TITANIUM
(Continued)
Ti-6Al-4V Titanium Alloy Adherends, P1700 Polysulfone Adhesive

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Bond Line Thickness inch	Percent Cohesive Failure (a)	Overlap Shear Strength, psi	Remarks
IB38- 1	No	Steel Screen/ 0.008	700	2	80	75	0.009	70	2765	
IB40- 2	No	"	700	2	80	75	0.011	95	2255	
IB40- 3	No	"	450	2	80	75	---	0	100	Bond failed during handling of specimen
IB40- 4	No	"	500	2	80	75	0.023	0	800	
IB40- 5	No	"	550	2	80	75	0.014	0	1655	
IB40- 6	No	"	600	2	80	75	0.014	0	1650	
IB40- 7	No	"	650	2	80	75	0.010	90	3385	
IB40- 8	No	"	750	2	80	75	0.012	100	3255	
IB40- 9	No	"	800	2	80	75	0.010	100	3620	
IB40-10	No	"	800	2	80	75	0.011	100	3675	
IB40-11	No	"	600	2	80	75	0.013	95	1950	Susceptor Screen Not Well Aligned
IB40-12	No	"	500	2	80	75	0.021	0	1030	
IB40-13	No	"	850	2	80	75	0.008	100	4560	
IB40-14	No	"	850	2	80	75	0.009	100	650	Adhesive degraded during bonding
IB40-15	No	"	850	2	80	75	0.008	100	2500	"
IB40-16	No	"	825	2	80	75	0.010	100	1025	Long heat-up; "

(a) Cohesive failure in thermoplastic adhesive; balance is adhesive failure on adherend

TABLE I - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED TITANIUM
(Concluded)
Ti-6Al-4V Titanium Alloy Adherends, P1700 Polysulfone Adhesive

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Bond Line Thickness inch	Percent Cohesive Failure (a)	Overlap Shear Strength, psi	Remarks
IB42- 1	No	Steel Screen/ 0.008	600	1	80	75	--	0	2060	
IB42- 2	No	"	600	1	80	75	--	0	1700	
IB42- 3	No	"	600	0.5	80	75	--	0	1815	
IB42- 4	No	"	600	0.5	80	75	--	0	1800	
IB42- 5	No	"	600	5	80	75	0.013	10	2500	
IB43- 1	No	"	700	0.5	80	75	0.014	20	2650	
IB43- 2	No	"	700	0.5	80	75	0.015	5	1740	
IB43- 3	No	"	700	1	80	75	0.012	10	2475	
IB43- 4	No	"	700	1	80	75	0.013	10	2455	
IB43- 5	No	"	700	5	80	75	0.012	40	2500	
IB43- 6	No	"	700	5	80	75	0.012	100	3945	
IB44- 1	No	"	800	0.25	80	75	0.013	50	2900	
IB44- 2	No	"	800	0.5	80	75	0.014	50	3220	
IB44- 3	No	"	800	0.5	80	75	0.012	30	3195	
IB44- 4	No	"	800	1	80	75	0.011	20	2600	Fixture problem
IB44- 5	No	"	800	1	80	75	0.012	60	3025	
IB44- 6	No	"	800	5	80	75	0.012	100	4075	
IB44- 7	No	"	800	5	80	75	0.010	100	4575	
IB39- 1	No	Nickel-200 Screen/ 0.005	560	--	80	75	0.008	100	4645	Maximum bond temperature possible for this configuration; long heat-up
IB39- 2	No	"	535	--	80	75	0.007	90	2495	"

(a) Cohesive failure in thermoplastic adhesive; balance is adhesive failure on adherend

TABLE II - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED HIGH TEMPERATURE COMPOSITES

Graphite Fiber/LaRC 160 Polyimide Composite Adherends, P1700 Polysulfone Adhesive

Specimen Number/ Layup	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Bond Line Thickness inch	Failure Surface Character(a), %C/%A/%D	Overlap Shear Strength, psi	Remarks
IB52- 1/*	No	Steel Screen/ 0.008	700	2	80	75	---	0/100/0	340	
IB52- 2	No	"	750	2	80	75	---	0/100/0	775	
IB52- 3	No	"	750	5	80	75	---	50/50/0	2625	
IB52- 4	No	"	700	5	80	75	---	40/60/0	2400	
IB52- 5	No	"	800	2	80	75	---	50/50/0	2645	
IB52- 6	No	"	800	5	80	75	---	100/0/0	3655	
IB52- 7	No	"	750	2	80	75	---	50/50/0	2270	
IB52- 8	No	"	800	5	80	75	0.008	75/25/0	2645	
IB52- 9	No	"	800	2	80	75	0.011	100/0/0	3050	
IB52-10	No	"	750	5	80	75	0.009	100/0/0	3900	

(a) %C = Percent cohesive failure in thermoplastic adhesive
%A = Percent adhesive failure on adherend surface
%D = Percent delamination of adherend

*$[0_5, \pm 30, 0_3]_S$

TABLE III - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED COMPOSITES

T-300 Graphite Fiber/5208 Epoxy Matrix Composite Adherends, HT-424 Epoxy Phenolic Adhesive on Fiberglass Cloth Carrier

Specimen Number/ Layup	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Bond Line Thickness, inch	Failure Surface Character(a), %C/%A/%D	Overlap Shear Strength, psi	Remarks
IB56- 1/ $[0_{16}]$	No	Steel Screen/ 0.008	400	2	80	75	---	50/50/0	2145	
IB56- 2	No	"	400	2	5	75	---	100/0/0	2780	
IB56- 3	No	"	400	5	5	75	---	100/0/0	3560	
IB56- 4	No	"	400	5	80	75	0.022	100/0/0	2070	
IB56- 5	No	"	400	5	5	75	0.026	100/0/0	2520	
IB56- 6	No	"	400	2	5	75	0.031	100/0/0	1845	
IB56- 7	No	"	450	5	5	75	0.031	100/0/0	2665	
IB56- 8	No	"	450	5	5	75	0.037	100/0/0	3050	
IB56- 9	No	"	450	2	5	75	0.035	100/0/0	3035	
IB56-10	No	"	450	2	5	75	0.030	100/0/0	2860	
IB56-11	No	"	450	2	10	75	0.030	100/0/0	3100	
IB56-12	No	"	450	2	20	75	0.026	100/0/0	2995	
IB56-13	No	"	450	2	10	75	0.024	100/0/0	3555	
IB56-14	No	"	450	2	20	75	0.024	100/0/0	3560	
IB56-15	No	"	450	2	40	75	0.023	100/0/0	3450	
IB56-16	No	"	450	2	40	75	0.021	100/0/0	3000	
IB56-17	No	"	450	2	80	75	0.021	100/0/0	3030	
IB56-18	No	"	450	2	80	75	0.023	100/0/0	3245	

(a) %C = Percent cohesive failure in thermoplastic adhesive
%A = Percent adhesive failure on adherend surface
%D = Percent delamination of adherend

TABLE IV - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF UNLIKE METALLIC ADHEREND SPECIMENS

Ti-6Al-4V Titanium Alloy and Alclad 2024-T3 Aluminum Alloy Adherends,
HT-424 Epoxy Phenolic Adhesive on Fiberglass Cloth Carrier

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Bond Line Thickness inch	Percent Cohesive Failure (a)	Overlap Shear Strength, psi	Remarks
IB50- 1	No	Steel Screen/ 0.008	450	5	80	75	0.026	100	3095	
IB50- 2	No	"	450	5	80	75	0.025	100	3175	
IB50- 3	No	"	450	2	80	75	0.024	100	2885	
IB50- 4	No	"	450	2	80	75	0.025	100	3045	
IB50- 5	No	"	400	5	80	75	0.020	100	3310	
IB50- 6	No	"	400	5	80	75	0.022	100	3380	
IB50- 7	No	"	400	2	80	75	0.022	100	3150	
IB50- 8	No	"	400	2	80	75	0.022	100	3060	
IB50- 9	No	"	350	5	80	75	0.021	100	3090	
IB50-10	No	"	350	5	80	75	0.022	100	3065	
IB51- 1	No	"	400	2	80	75	0.022	100	3600	Postcured in oven at 350°F, 1 hour
IB51- 2	No	"	400	2	80	75	0.024	100	3655	"

(a) Cohesive failure in thermoplastic adhesive; balance is adhesive failure on adherend

TABLE V - COMPARISON OF RAPID ADHESIVE BONDING WITH PRESS BONDING OVERLAP SHEAR STRENGTHS

Ti-6Al-4V Titanium Alloy Adherends, BDSDA/APB Thermoplastic Adhesive

BONDING EQUIPMENT	BONDING CONDITIONS				OVERLAP SHEAR STRENGTH* AT ROOM TEMPERATURE, psi
	BONDING PRESSURE, psi	BONDING TEMPERATURE, °F	HOLD TIME AT BOND.TEMP., min.	HEATING RATE TO BOND.TEMP., °F/min.	
Laboratory Press with Heated Platens	300	600	15	9	5900 5625 6190 5685 Avg. 5850
Laboratory Press with Pre-Heated Platens	300	600	15	40	6450 6250 6545 5920 Avg. 6291
Rapid Adhesive Bonding	50	570	2	275	6960 6895 Avg. 6928

*Per ASTM D1002-72

TABLE VI - ADHESIVES INVESTIGATED WHICH PRODUCE STRONG BONDS IN RAB SPECIMENS

THERMOSETTING ADHESIVES

ADHESIVE DESIGNATION (MATERIAL CLASS)	ADHESIVE SUPPLIER	BONDING CONDITIONS			
		HEATING RATE TO BOND.TEMP., °F/min.	BONDING TEMPERATURE, °F	BONDING PRESSURE, psi	HOLD TIME AT BOND.CONDITION, min.
HT-424 (Epoxy-phenolic)	American Cyanamid	1200	450	40	2
Scotchweld EC-1386 (Epoxy paste)	3M	80	415	10	3
AF-163 (Elastomeric mod.Epoxy)	3M	1200	350	10	2
Bismaleimide of siloxane diamine*	NASA - Langley	300	535	100	2
General purpose epoxy	Hardman	1200	450	50	2

*Experimental adhesive, not commercially available

TABLE VI - ADHESIVES INVESTIGATED WHICH PRODUCE STRONG BONDS IN RAB SPECIMENS
(Continued)
THERMOPLASTIC ADHESIVES

ADHESIVE DESIGNATION (MATERIAL CLASS)	ADHESIVE SUPPLIER	BONDING CONDITIONS			
		HEATING RATE TO BOND.TEMP., °F/min.	BONDING TEMPERATURE, °F	BONDING PRESSURE, psi	HOLD TIME AT BOND.CONDITION, min.
P-1700 (Polysulfone)	Union Carbide	1200	750	80	2
$PISO_2$* (Polyimidesulfone)	NASA - Langley	1200	635	50	2
TPI (Thermoplastic polyimide)	Gulf	1200	650	200	2
PEEK (Polyetheretherketone)	ICI	1200	750	50	2
PPQ* (Polyphenylquinoxaline)	NASA - Langley	1200	500	100	5

*Experimental adhesive, not commercially available

TABLE VI - ADHESIVES INVESTIGATED WHICH PRODUCE STRONG BONDS IN RAB SPECIMENS (Continued)

THERMOPLASTIC ADHESIVES (Continued)

ADHESIVE DESIGNATION (MATERIAL CLASS)	ADHESIVE SUPPLIER	BONDING CONDITIONS			
		HEATING RATE TO BOND.TEMP., °F/min.	BONDING TEMPERATURE, °F	BONDING PRESSURE, psi	HOLD TIME AT BOND.CONDITION, min.
Ultem (Polyetherimide)	General Electric	1200	625	5	2
Silane end capped polyimide*	NASA - Langley	300	535	100	2
Linear thermoplastic polyimide with silane additions*	NASA - Langley	300	535	100	2
BDSDA + APB* (Hot-melt polyimide)	NASA - Langley	275	570	50	2

*Experimental adhesive, not commercially available

TABLE VII - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED TITANIUM AND COMPOSITE

AF-163 Elastomeric Modified Epoxy Film Adhesive

Ti-6Al-4V Titanium Alloy Adherends

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Overlap Shear Strength, psi	Remarks
IB79- 1	No	PSS*/ 0.005	350	2	10	75	5625	All bonds made at 1200°F/min heating rate to bonding temperature and rapid cool from bonding temperature
IB79- 2	No	"	350	2	10	75	6100	
IB79- 3	No	"	350	2	10	75	5370	
IB79- 4	No	"	350	2	10	75	5750	
IB79- 5	No	"	350	2	10	75	5400	
IB79- 6	No	"	350	2	10	180	2580	
IB79- 7	No	"	350	2	10	180	3450	
IB79- 8	No	"	350	2	10	180	3110	
IB79- 9	No	"	350	2	10	180	2300	
IB79-10	No	"	350	2	10	180	2655	
IB79-11	No	"	350	2	10	75	2680	LSS test after 72-hour water boil
IB79-12	No	"	350	2	10	75	2200	"
IB79-13	No	"	350	2	10	180	420	"
IB79-14	No	"	350	2	10	180	660	

T-300 Graphite Fiber/5208 Epoxy Matrix Composite Adherends

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Overlap Shear Strength, psi	Remarks
IB79-21	No	PSS*/ 0.005	350	2	10	75	4440	Composite adherend delamination failure
IB79-22	No	"	350	2	10	75	4200	"
IB79-23	No	"	350	2	10	75	3800	

*Perforated stainless steel foil

TABLE VIII - RAPID ADHESIVE BONDING OVERLAP SHEAR STRENGTH OF BONDED TITANIUM

Ti-6Al-4V Titanium Alloy Adherends; EC-1386 Epoxy Paste Adhesive

Specimen Number	Primed Specimen	Susceptor Material/ Thickness, inch	Bonding Temperature, °F	Hold Time at Bond Temp., min.	Bond Pressure, psi	Shear Test Temp., °F	Overlap Shear Strength, psi	Remarks
IB81- 1	No	PSS*/ 0.005	415	2	10	75	5990	All bonds made at 80°F/min heating rate to bonding temperature and rapid cool from bonding temperature
IB81- 2	No	"	415	2	10	75	6010	
IB81- 3	No	"	415	2	10	75	6150	
IB81- 4	No	"	415	2	10	75	6500	
IB81- 5	No	"	415	2	10	75	6340	
IB81- 6	No	"	415	2	10	180	>5350	No adhesive failure; tests were terminated due to bearing failures at adherend loading holes
IB81- 7	No	"	415	2	10	180	>4915	
IB81- 8	No	"	415	2	10	180	>4820	
IB81- 9	No	"	415	2	10	180	>4925	"
IB81-10	No	"	415	2	10	180	>4995	"
IB81-11	No	"	415	2	10	75	2420	LSS test after 72-hour water boil
IB81-12	No	"	415	2	10	75	2205	"
IB81-13	No	"	415	2	10	180	2370	"
IB81-14	No	"	415	2	10	180	1915	"

*Perforated stainless steel foil

RAPID ADHESIVE BONDING

SPECIFIC TARGET CRITERIA

PARAMETER	NEEDS	WANTS
LOW TEMPERATURE ADHESIVE MECHANICAL PROPERTIES		
o FAILURE MODE	COHESIVE	COHESIVE
o TI/TI LAP SHEAR @ R.T.	> 3000 PSI	> 6000 PSI
o COMPOSITE/COMPOSITE LAP SHEAR @ R.T.	> 2000 PSI	> 4000 PSI
HIGH TEMPERATURE ADHESIVE MECHANICAL PROPERTIES		
o FAILURE MODE	COHESIVE	COHESIVE
o TI/TI LAP SHEAR @ R.T.	> 3000 PSI	> 5000 PSI
o TI/TI LAP SHEAR @ 260C	> 2000 PSI	> 3000 PSI
o COMPOSITE/COMPOSITE LAP SHEAR @ R.T.	> 2000 PSI	> 4000 PSI
o COMPOSITE/COMPOSITE LAP SHEAR @ 260C	> 1500 PSI	> 3000 PSI

FIG. 1A

SPECIFIC TARGET CRITERIA (CONTINUED)

PARAMETER	NEEDS	WANTS
BONDING CONDITIONS		
o SPOT BONDING TIME	< 2 MINUTES	< 1 MINUTE
o SEAM BONDING RATE	> 3 IN/MIN	> 6 IN/MIN
o BONDING PRESSURE	< 100 PSI	< 25 PSI
o ADHEREND DIMENSIONS	> 2 FT. LONG	> 10 FT. LONG
	> 2 FT. WIDE	> 10 FT. WIDE
	> 1/8 IN. THICK	> 3/8 IN. THICK
o BOND DIMENSIONS	> 2 FT. LONG	> 10 FT. LONG
	> 1/4 IN. WIDE	> 1/2 IN. WIDE
	< 20 MILS THICK	< 10 MILS THICK
o POWER		
– VOLTS	< 110V	< 24V
– AMPS	< 10A	< 5A
– WATT-HOURS/INCH OF BOND	< 25 W-H/IN	< 10W-H/IN
CONTINUOUS MONITORING REQUIREMENTS		
o BOND TEMPERATURE	> ± 10°F	> ± 20°F
o ADHEREND TEMPERATURE	> ± 10°F	> ± 20°F
o POWER INPUT	> ± .5V, ± 0.1A	> ± 1 VOLT, ± 0.1 AMP
o BOND PRESSURE	> ± 2 PSI	± 10 PSI

FIG. 1B

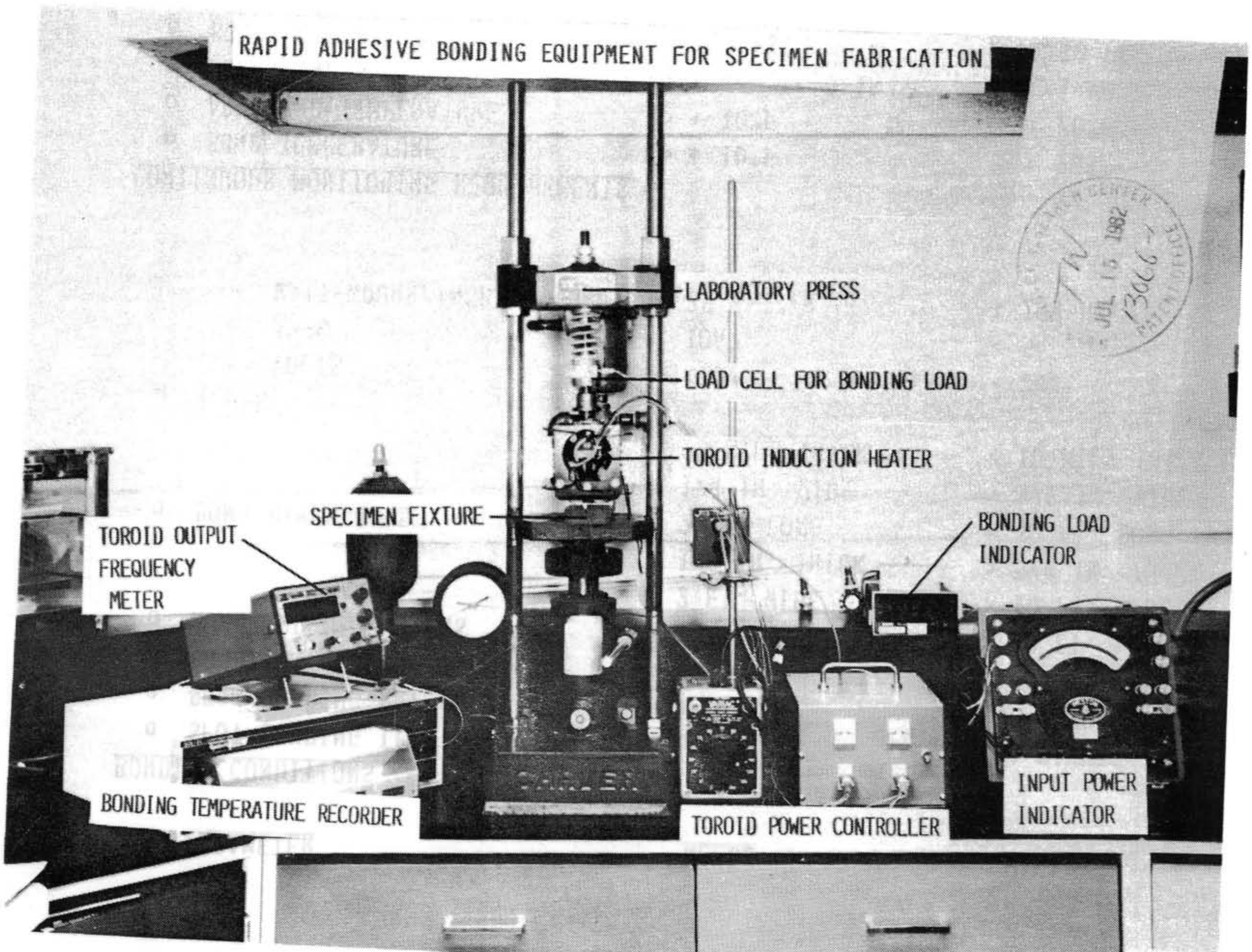

RAPID ADHESIVE BONDING EQUIPMENT FOR SPECIMEN FABRICATION
LABORATORY PRESS
LOAD CELL FOR BONDING LOAD
TOROID INDUCTION HEATER
SPECIMEN FIXTURE
TOROID OUTPUT FREQUENCY METER
BONDING LOAD INDICATOR
BONDING TEMPERATURE RECORDER
TOROID POWER CONTROLLER
INPUT POWER INDICATOR

FIG. 2

L-82-2,238

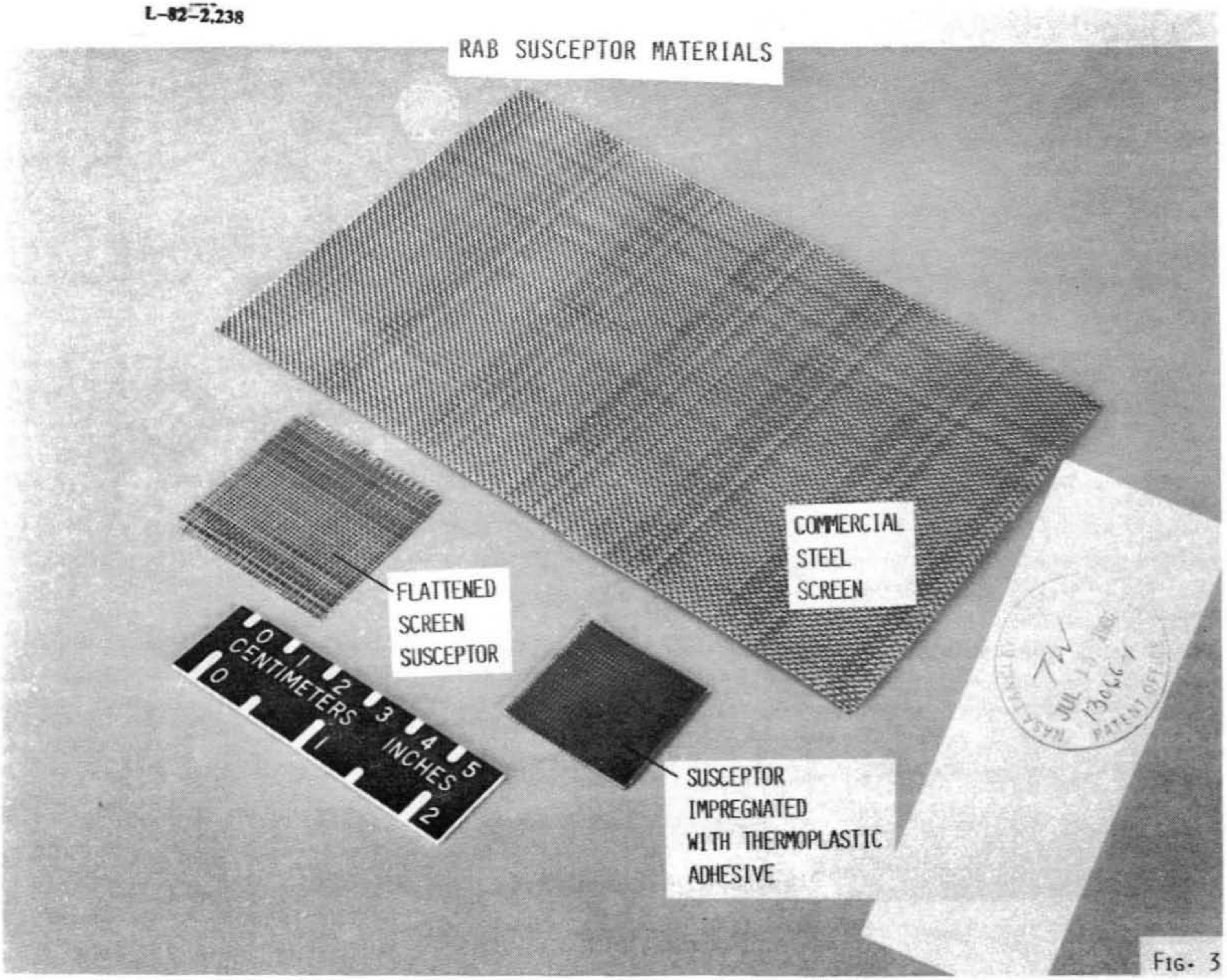


FIG. 3

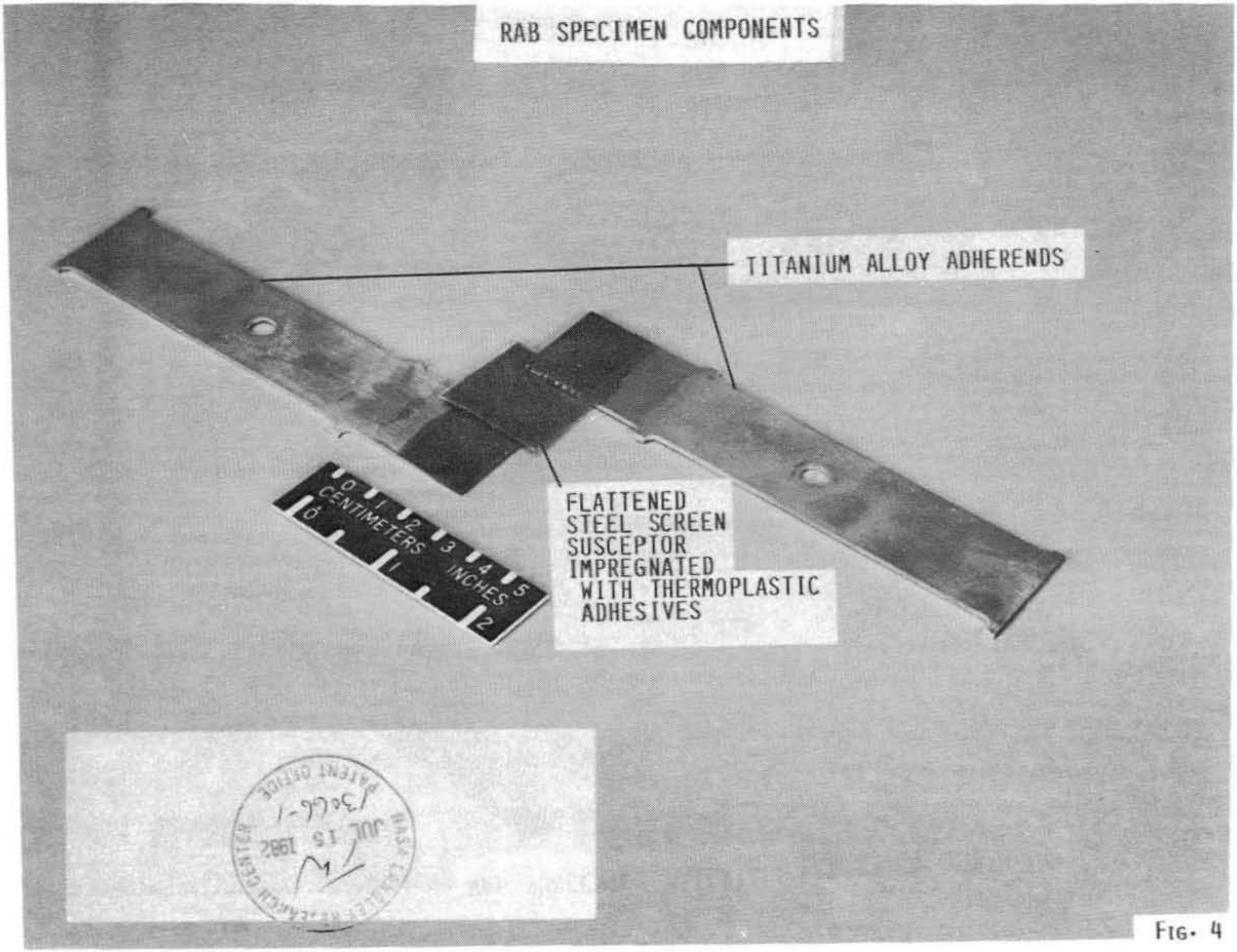

RAB SPECIMEN COMPONENTS
TITANIUM ALLOY ADHERENDS
FLATTENED STEEL SCREEN SUSCEPTOR IMPREGNATED WITH THERMOPLASTIC ADHESIVES
CENTIMETERS
INCHES

FIG. 4

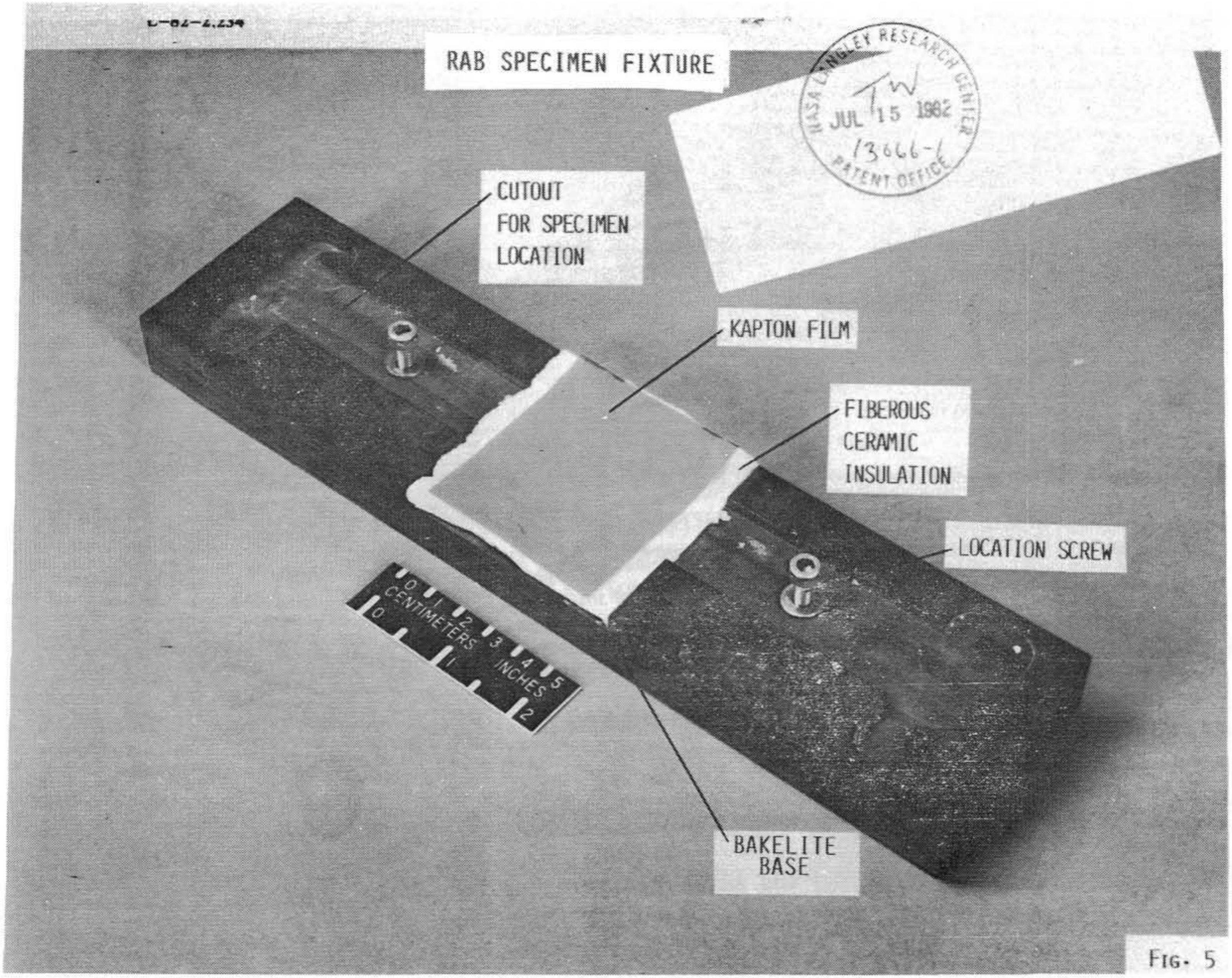

L-82-2,234
RAB SPECIMEN FIXTURE
NASA LANGLEY RESEARCH CENTER
JUL 15 1982
13666-1
PATENT OFFICE
CUTOUT
FOR SPECIMEN
LOCATION
KAPTON FILM
FIBEROUS
CERAMIC
INSULATION
LOCATION SCREW
CENTIMETERS
INCHES
BAKELITE
BASE

FIG. 5

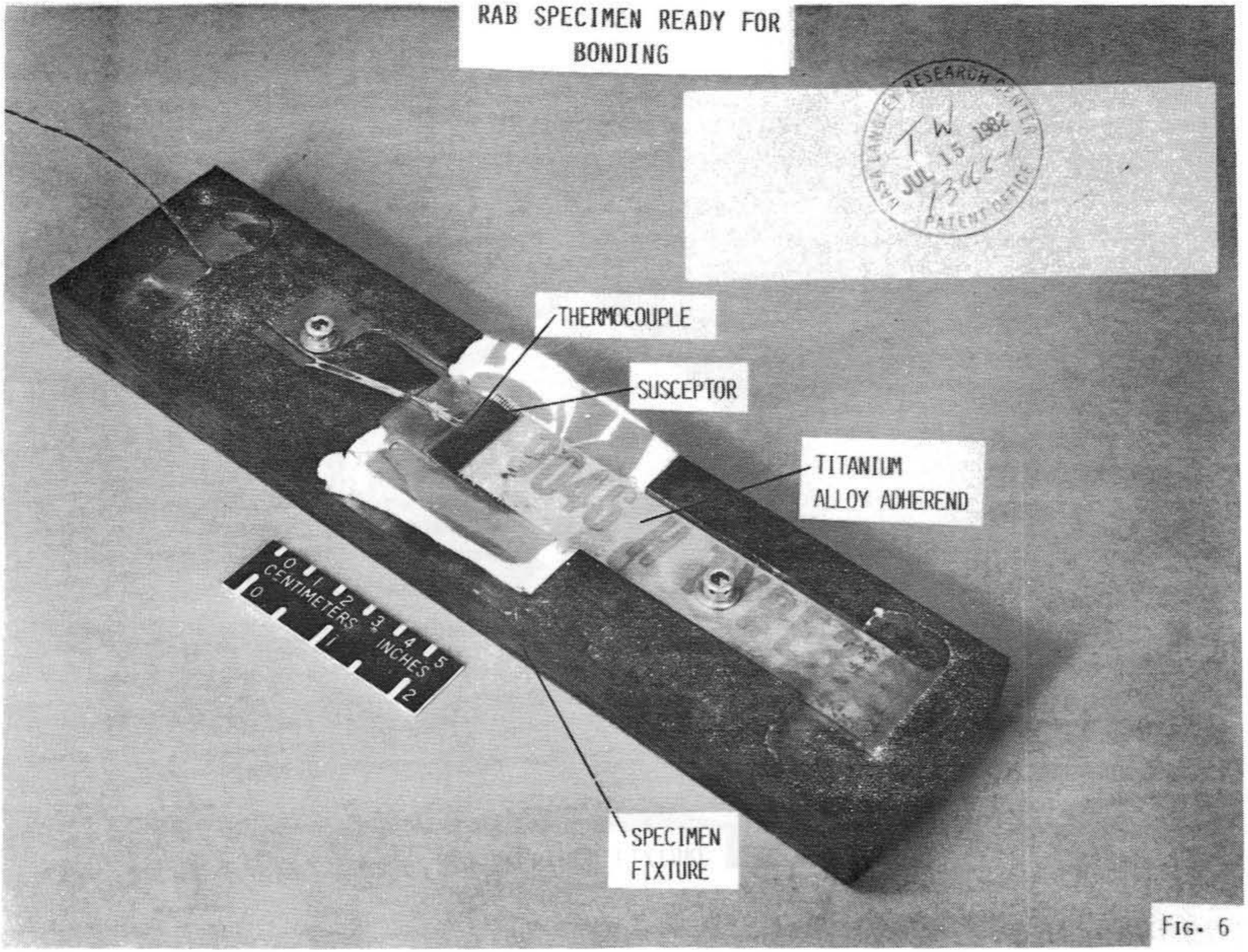
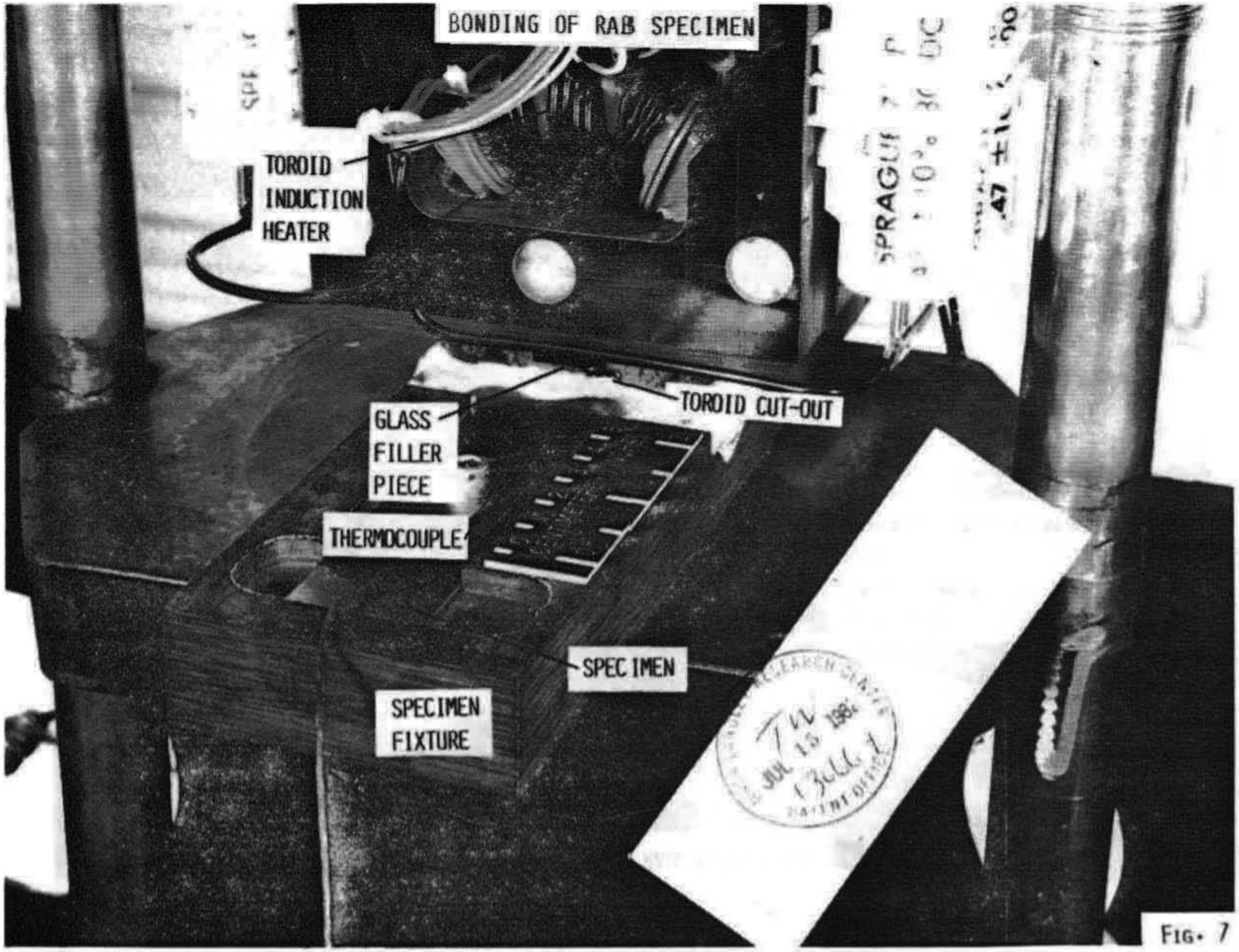

RAB SPECIMEN READY FOR BONDING
NASA LANGLEY RESEARCH CENTER
JUL 15 1982
PATENT OFFICE
THERMOCOUPLE
SUSCEPTOR
TITANIUM ALLOY ADHEREND
CENTIMETERS
INCHES
SPECIMEN FIXTURE

FIG. 6



BONDING OF RAB SPECIMEN
TOROID INDUCTION HEATER
TOROID CUT-OUT
GLASS FILLER PIECE
THERMOCOUPLE
SPECIMEN
SPECIMEN FIXTURE

FIG. 7

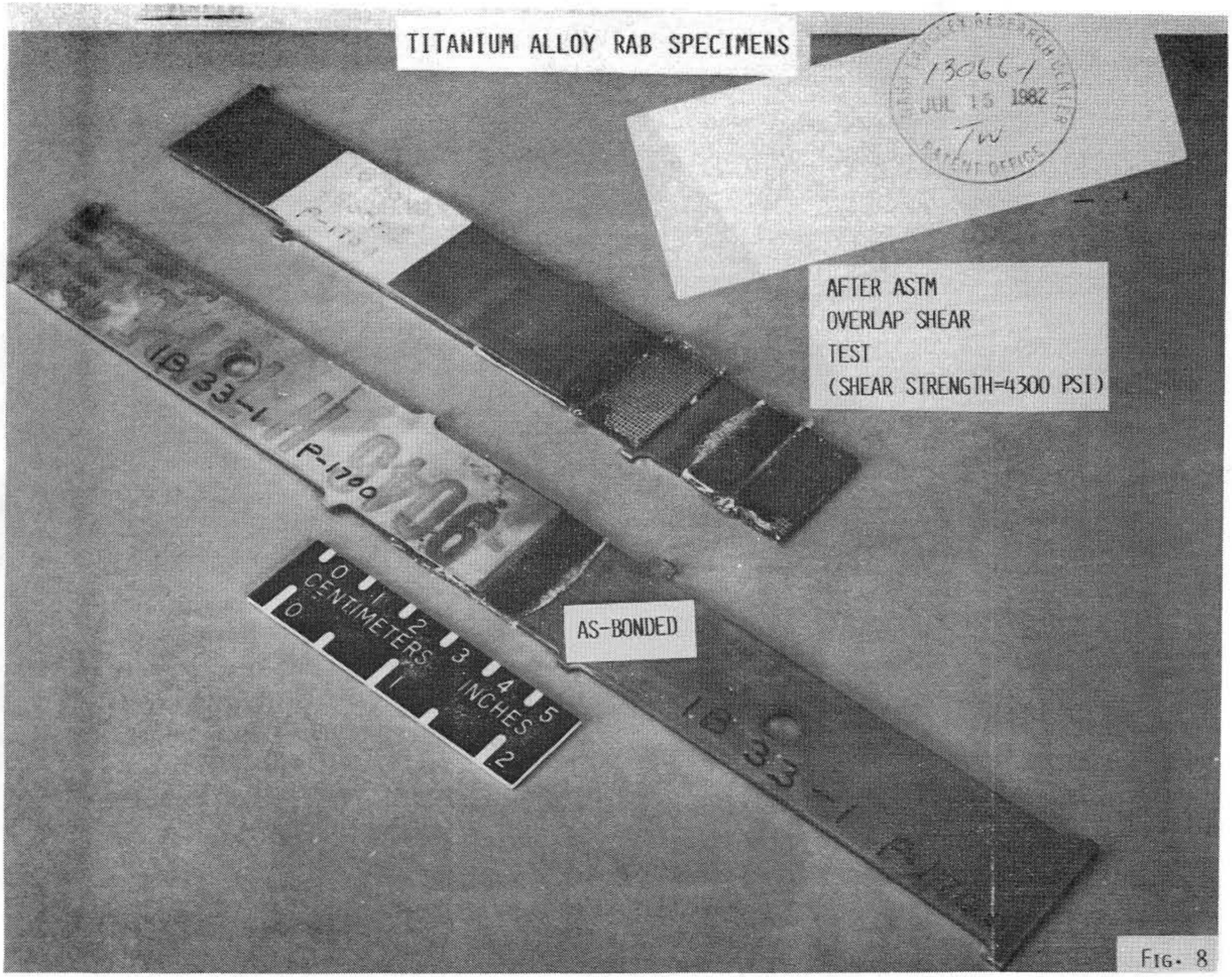

TITANIUM ALLOY RAB SPECIMENS
AFTER ASTM
OVERLAP SHEAR
TEST
(SHEAR STRENGTH=4300 PSI)
AS-BONDED
1B 33-1
P-1700
CENTIMETERS
INCHES
13066-1
JUL 15 1982

FIG. 8

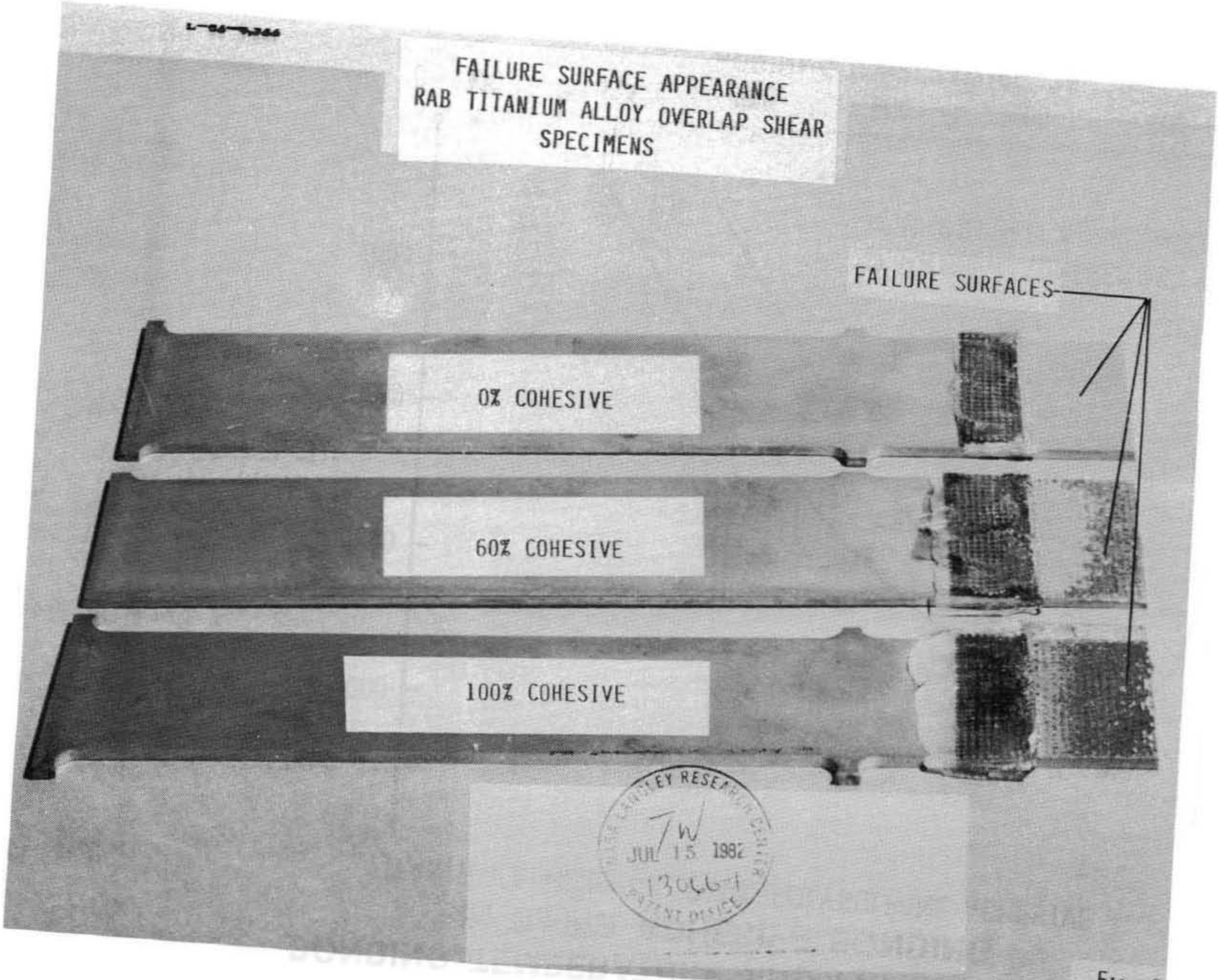

FAILURE SURFACE APPEARANCE
RAB TITANIUM ALLOY OVERLAP SHEAR
SPECIMENS
FAILURE SURFACES
0% COHESIVE
60% COHESIVE
100% COHESIVE
JUL 15 1982

FIG. 9

BONDING TEMPERATURE AND PRIMING EFFECTS IN RAPID ADHESIVE BONDING

TITANIUM ADHERENDS, P1700 POLYSULFONE ADHESIVE

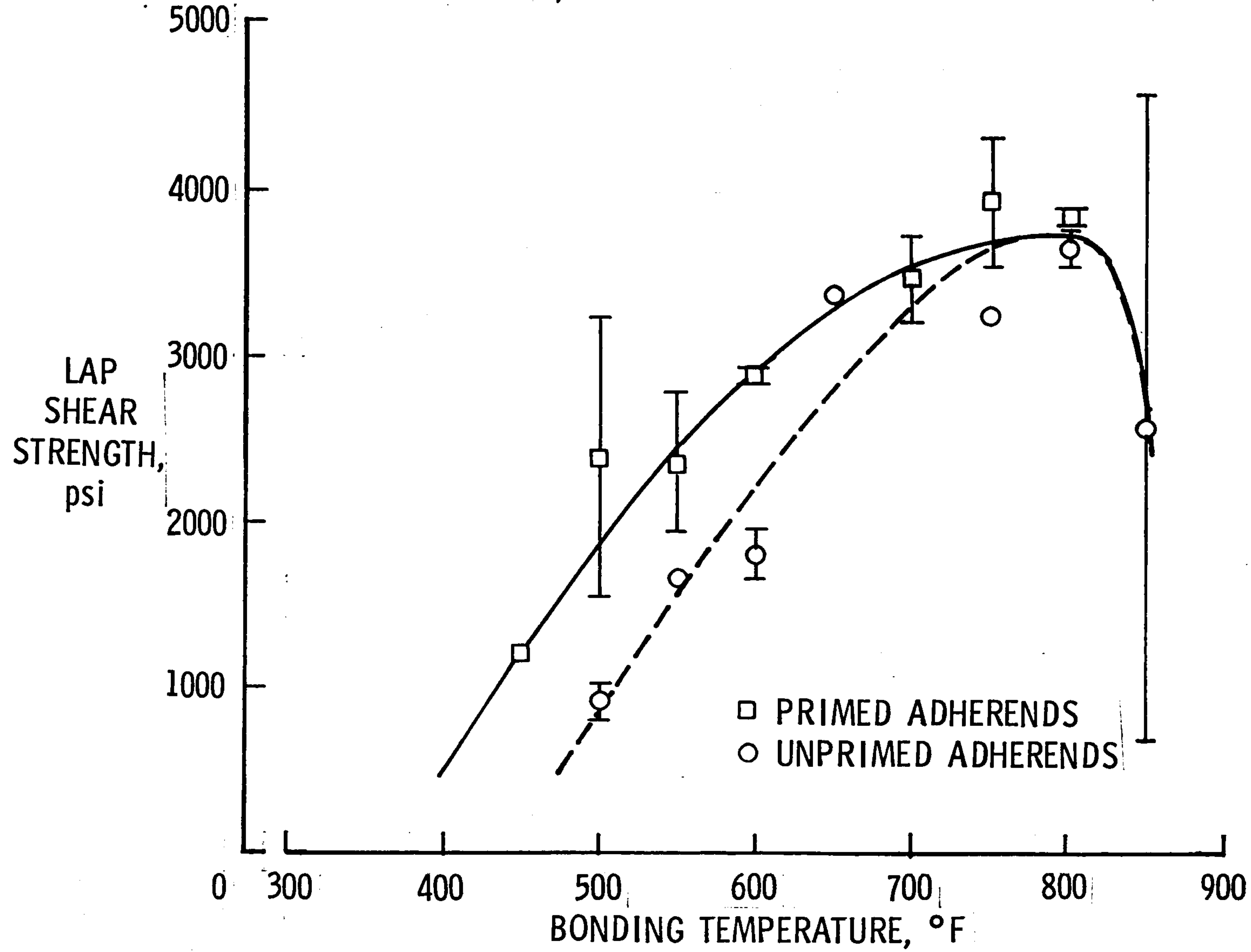


FIG. 10

BONDING PRESSURE EFFECTS IN RAPID ADHESIVE BONDING

GRAPHITE/EPOXY (T300/5208) ADHERENDS, HT-424 ADHESIVE

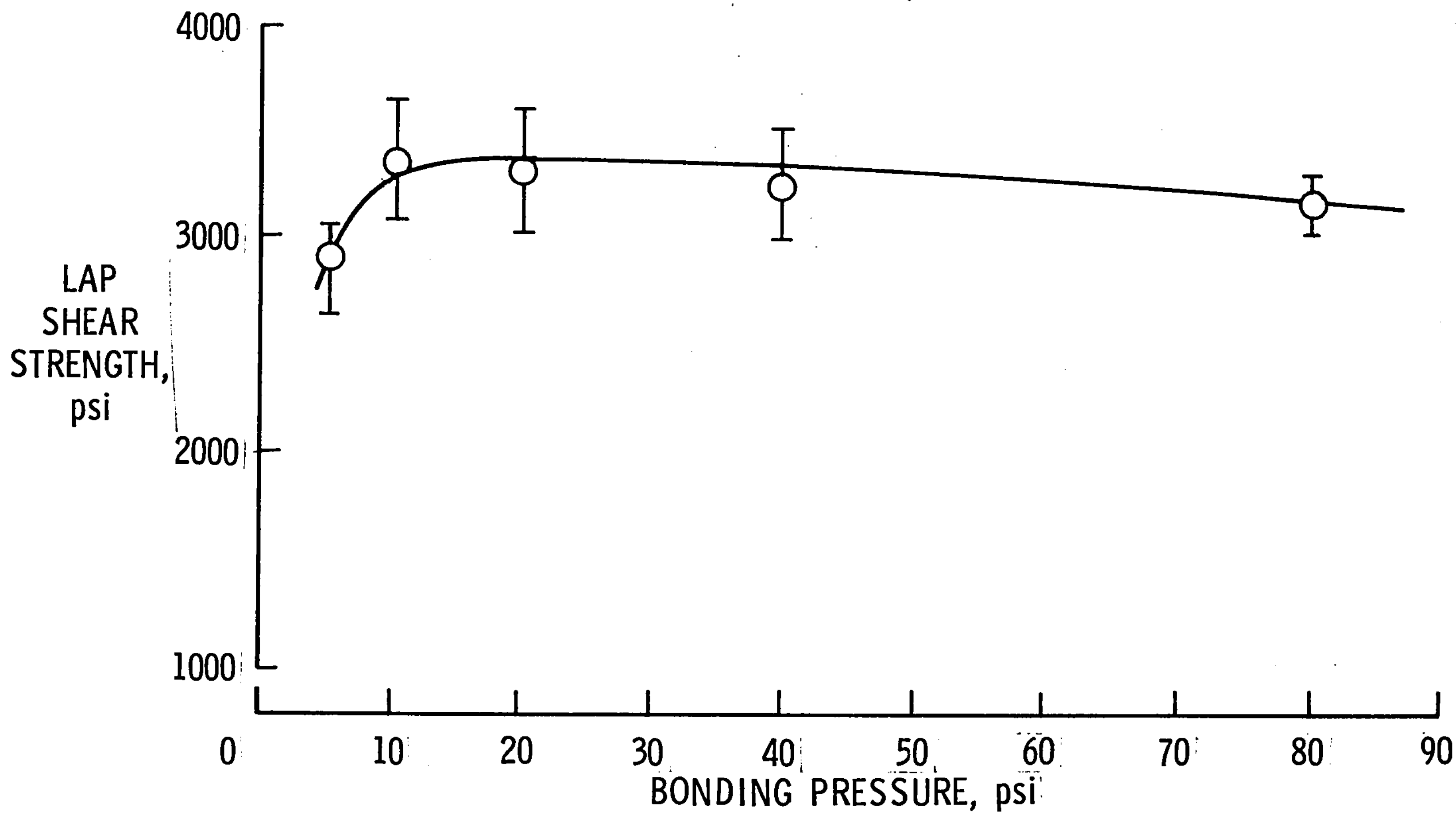


FIG. 11

COMPARISON OF BONDING TECHNIQUES

TITANIUM ADHERENDS, EXPERIMENTAL THERMOPLASTIC ADHESIVE

(ASTM D1002-72 R.T. LAP SHEAR TEST)

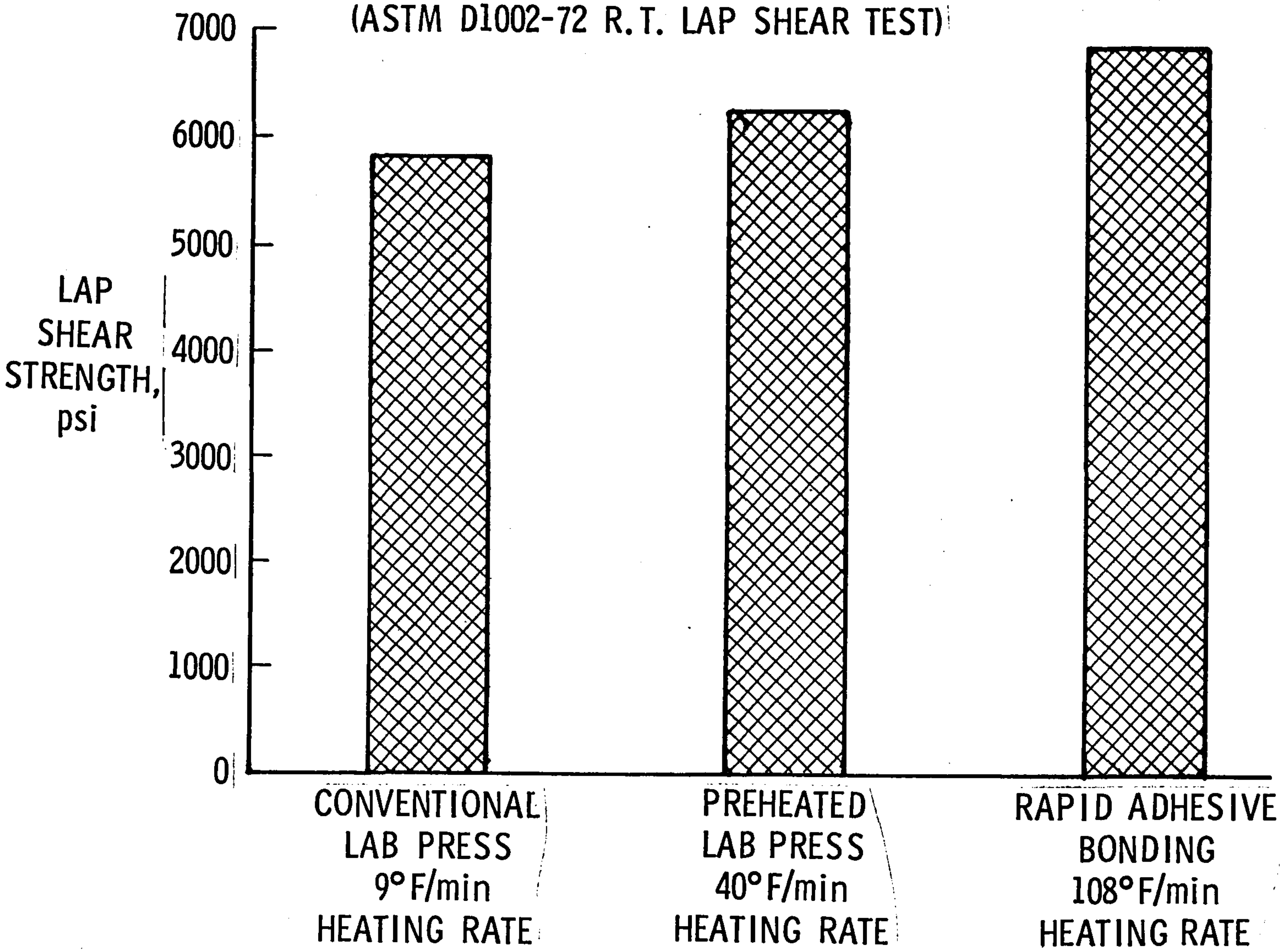


FIG. 12

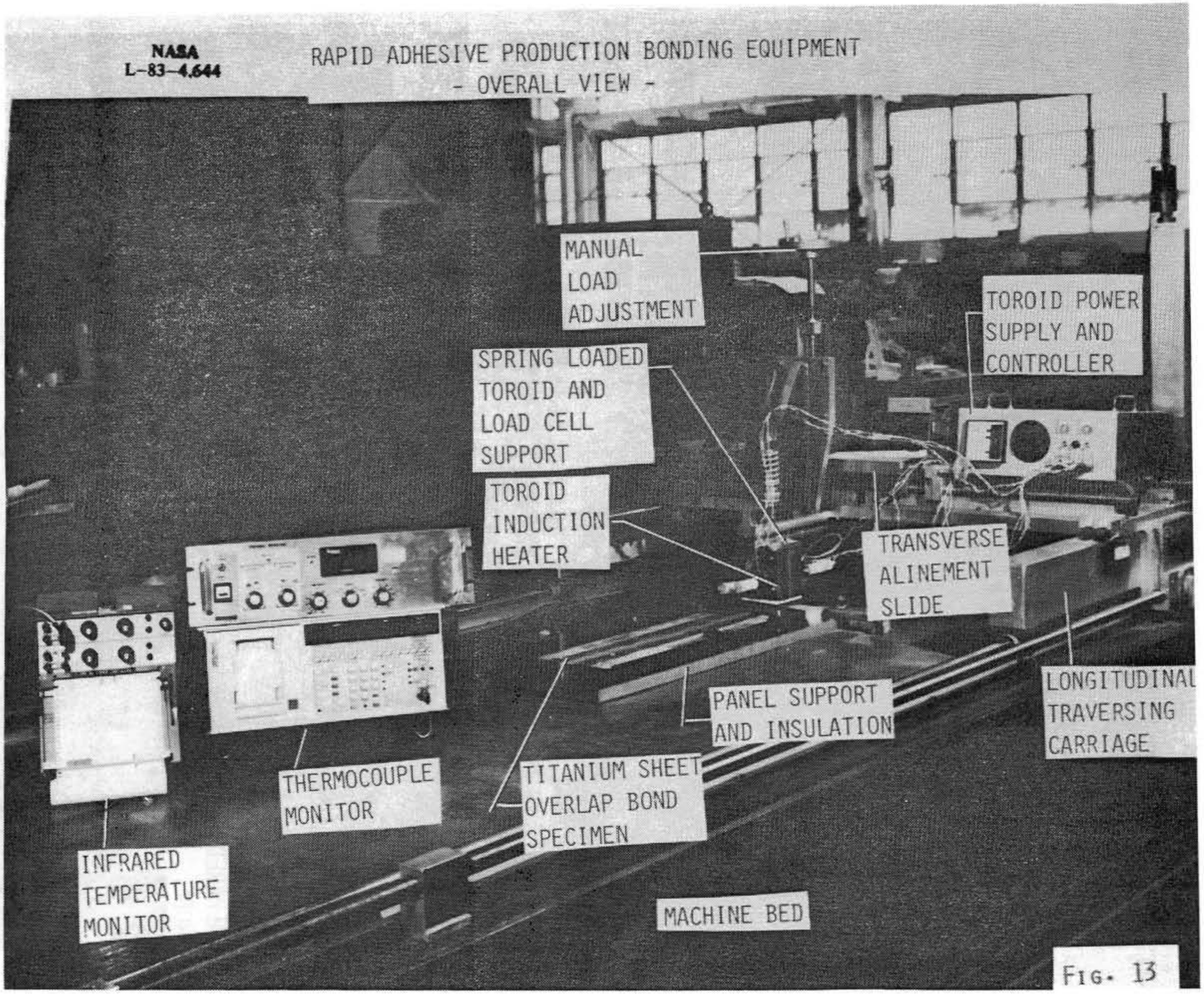

NASA
L-83-4,644
RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
- OVERALL VIEW -
MANUAL LOAD ADJUSTMENT
TOROID POWER SUPPLY AND CONTROLLER
SPRING LOADED TOROID AND LOAD CELL SUPPORT
TOROID INDUCTION HEATER
TRANSVERSE ALINEMENT SLIDE
LONGITUDINAL TRAVERSING CARRIAGE
PANEL SUPPORT AND INSULATION
THERMOCOUPLE MONITOR
TITANIUM SHEET OVERLAP BOND SPECIMEN
INFRARED TEMPERATURE MONITOR
MACHINE BED

FIG. 13

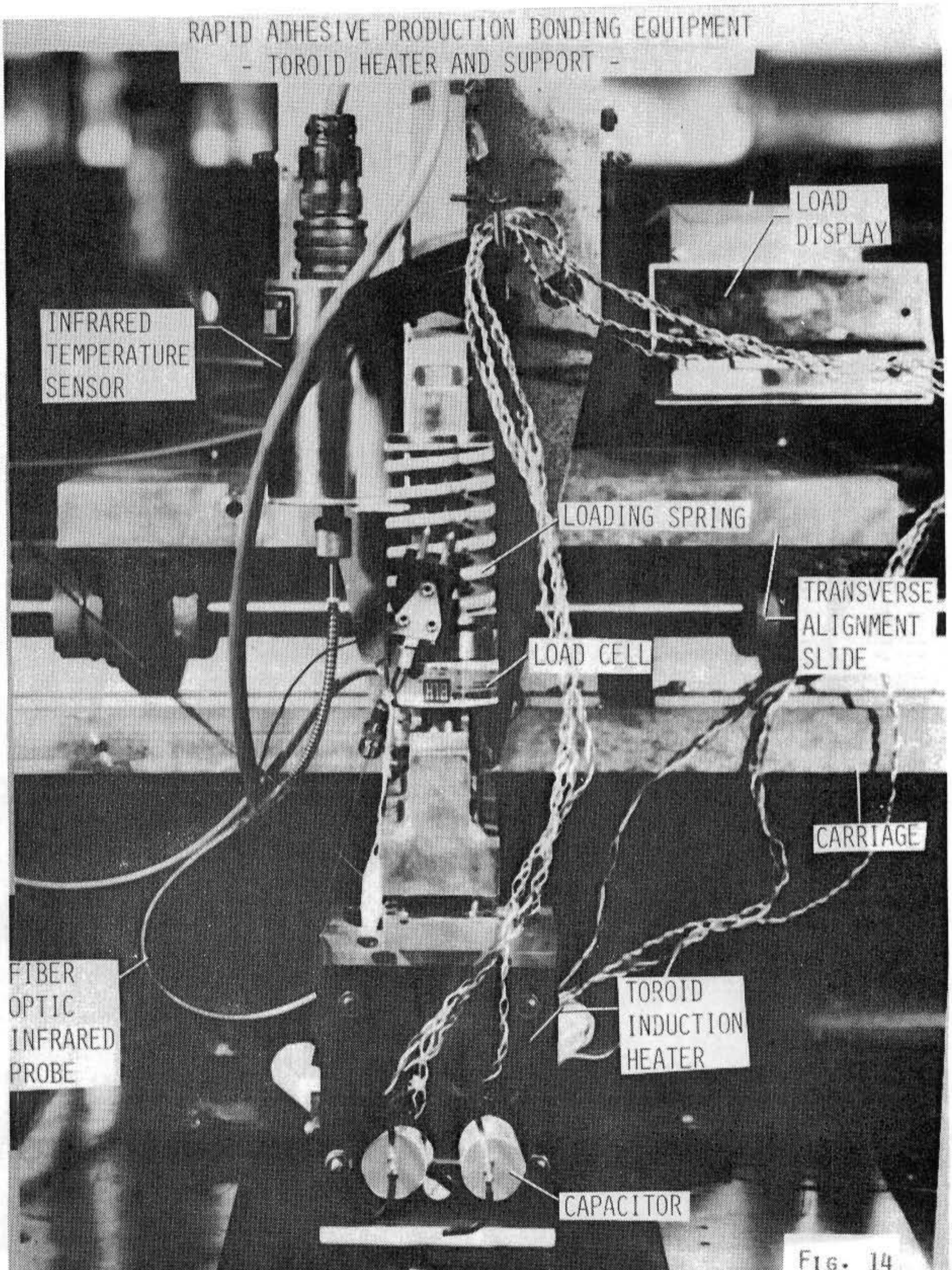

RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
- TOROID HEATER AND SUPPORT -
LOAD DISPLAY
INFRARED TEMPERATURE SENSOR
LOADING SPRING
TRANSVERSE ALIGNMENT SLIDE
LOAD CELL
CARRIAGE
FIBER OPTIC INFRARED PROBE
TOROID INDUCTION HEATER
CAPACITOR

FIG. 14

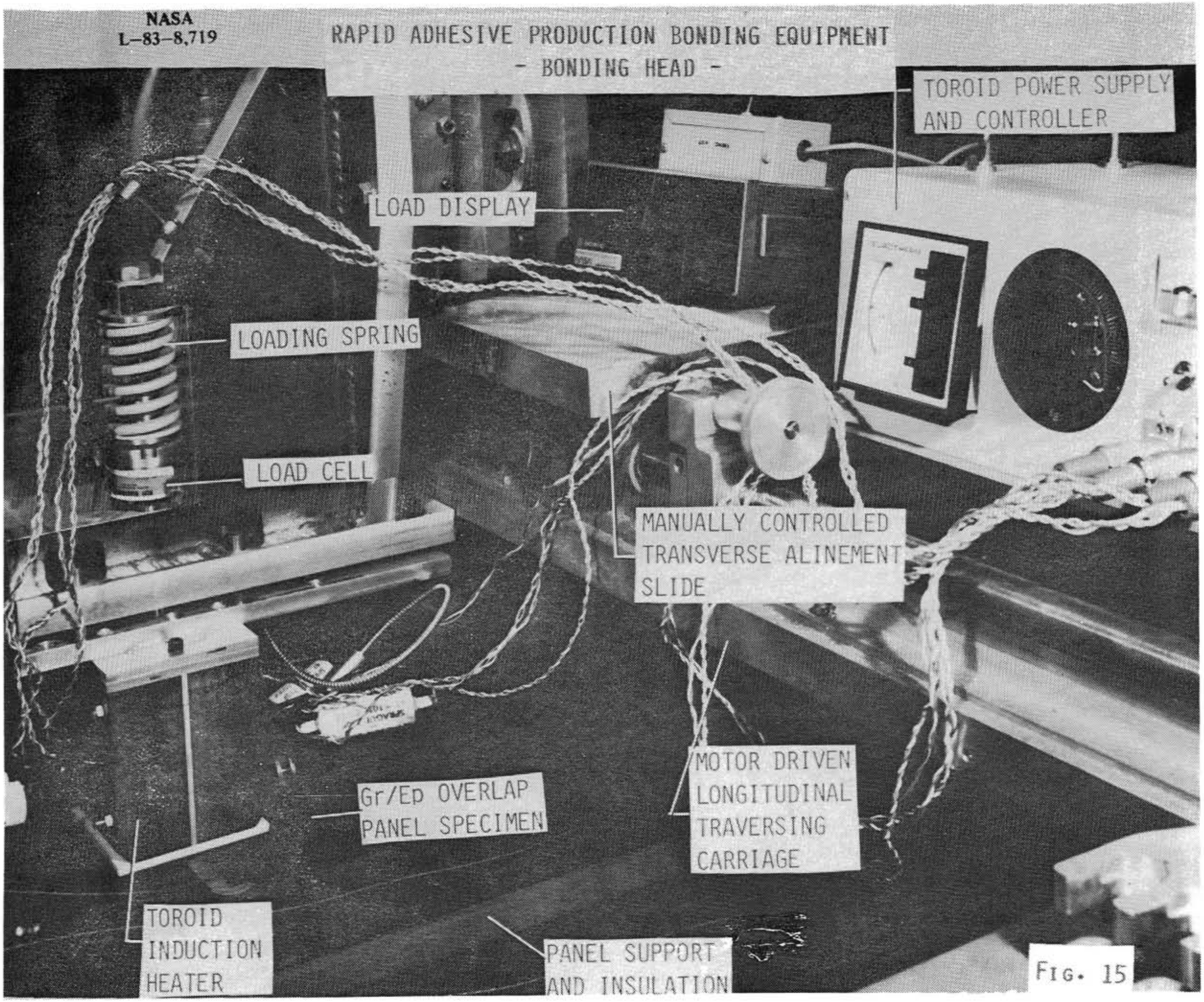

NASA
L-83-8,719
RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
- BONDING HEAD -
TOROID POWER SUPPLY AND CONTROLLER
LOAD DISPLAY
LOADING SPRING
LOAD CELL
MANUALLY CONTROLLED TRANSVERSE ALINEMENT SLIDE
MOTOR DRIVEN LONGITUDINAL TRAVERSING CARRIAGE
Gr/Ep OVERLAP PANEL SPECIMEN
TOROID INDUCTION HEATER
PANEL SUPPORT AND INSULATION

FIG. 15

NASA
L-83-4,642

RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
- FIBER OPTIC INFRARED TEMPERATURE PROBE -

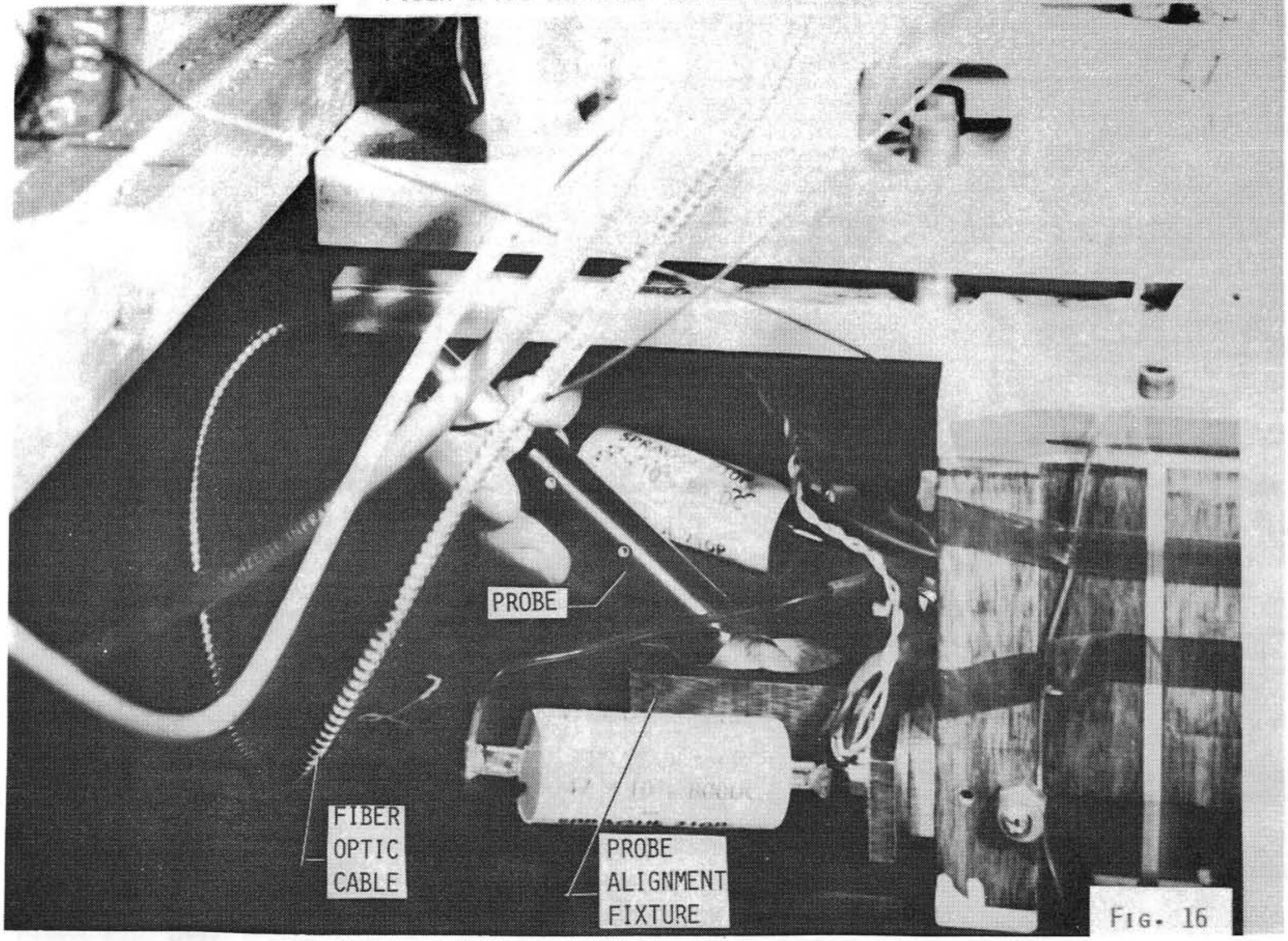


FIG. 16

NASA
L-83-4,639

RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
- START OF BOND -

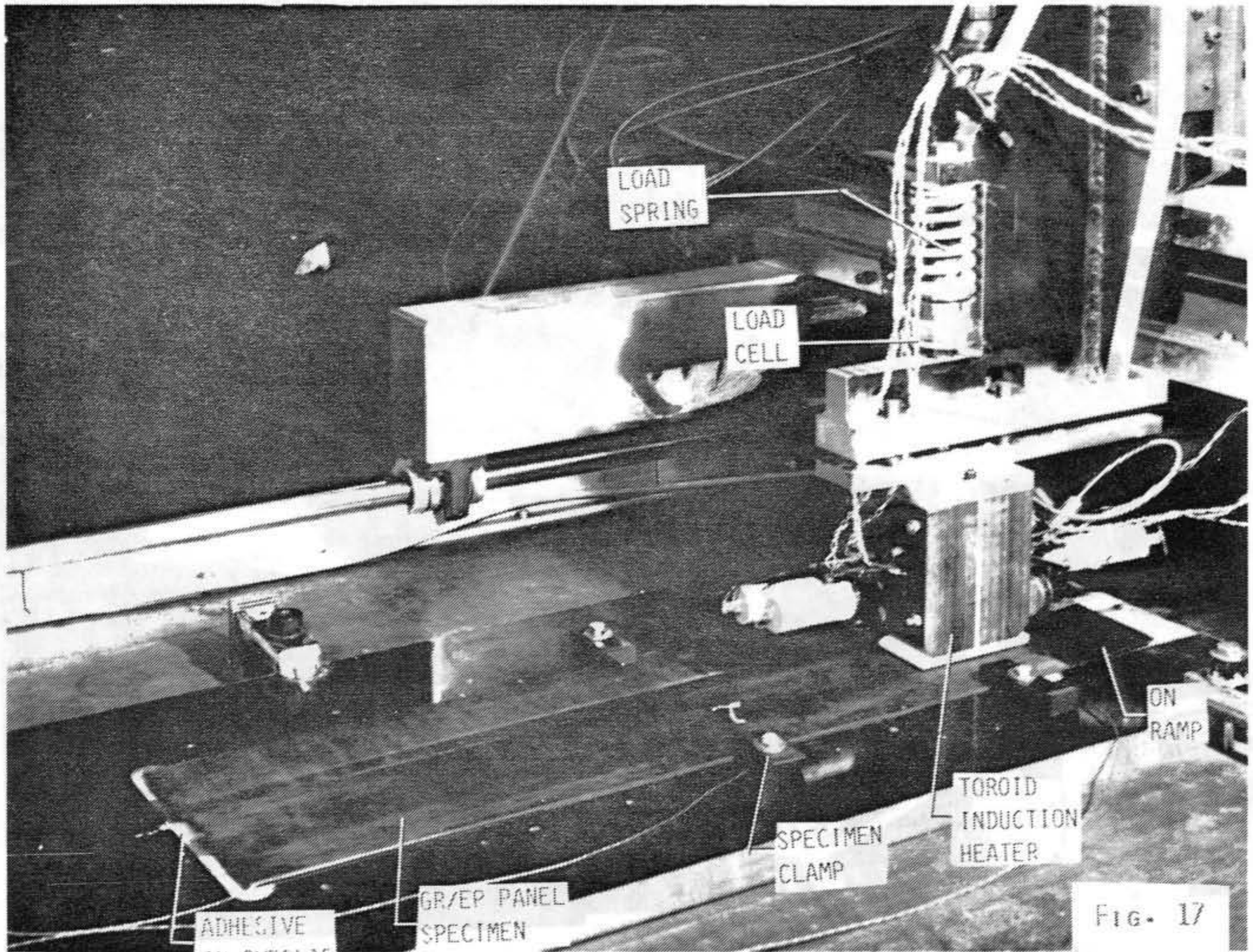


FIG. 17

L-83-4,641

RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT

- BOND IN PROGRESS -

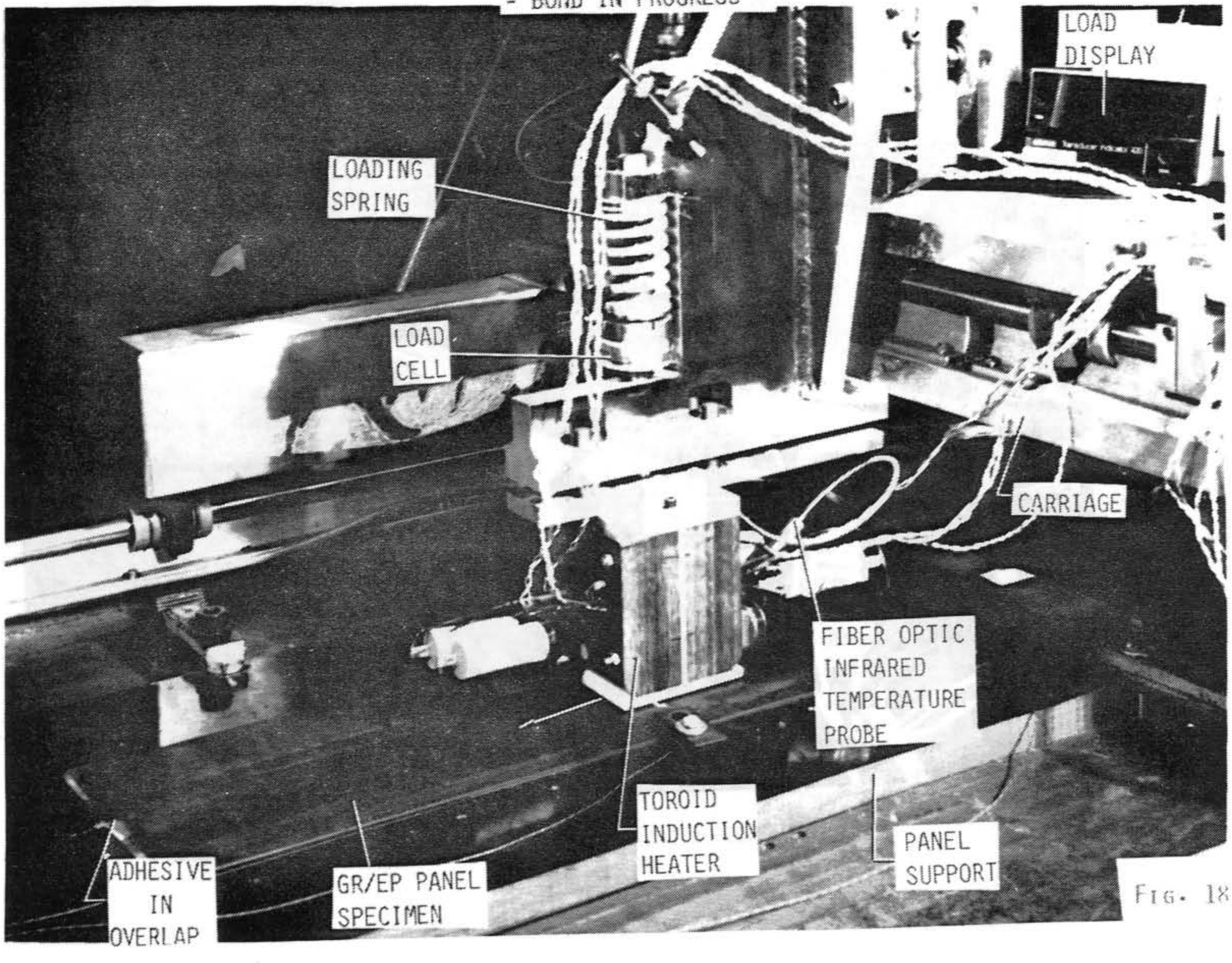


FIG. 18


L-83-7,554
RAPID ADHESIVE PRODUCTION BONDING
Ti-6Al-4V TITANIUM ALLOY PANELS
LARC-TPI ADHESIVE
STEEL SCREEN
SUSCEPTOR IN BOND LINE
NO SUSCEPTOR
IN BOND LINE

FIG. 19

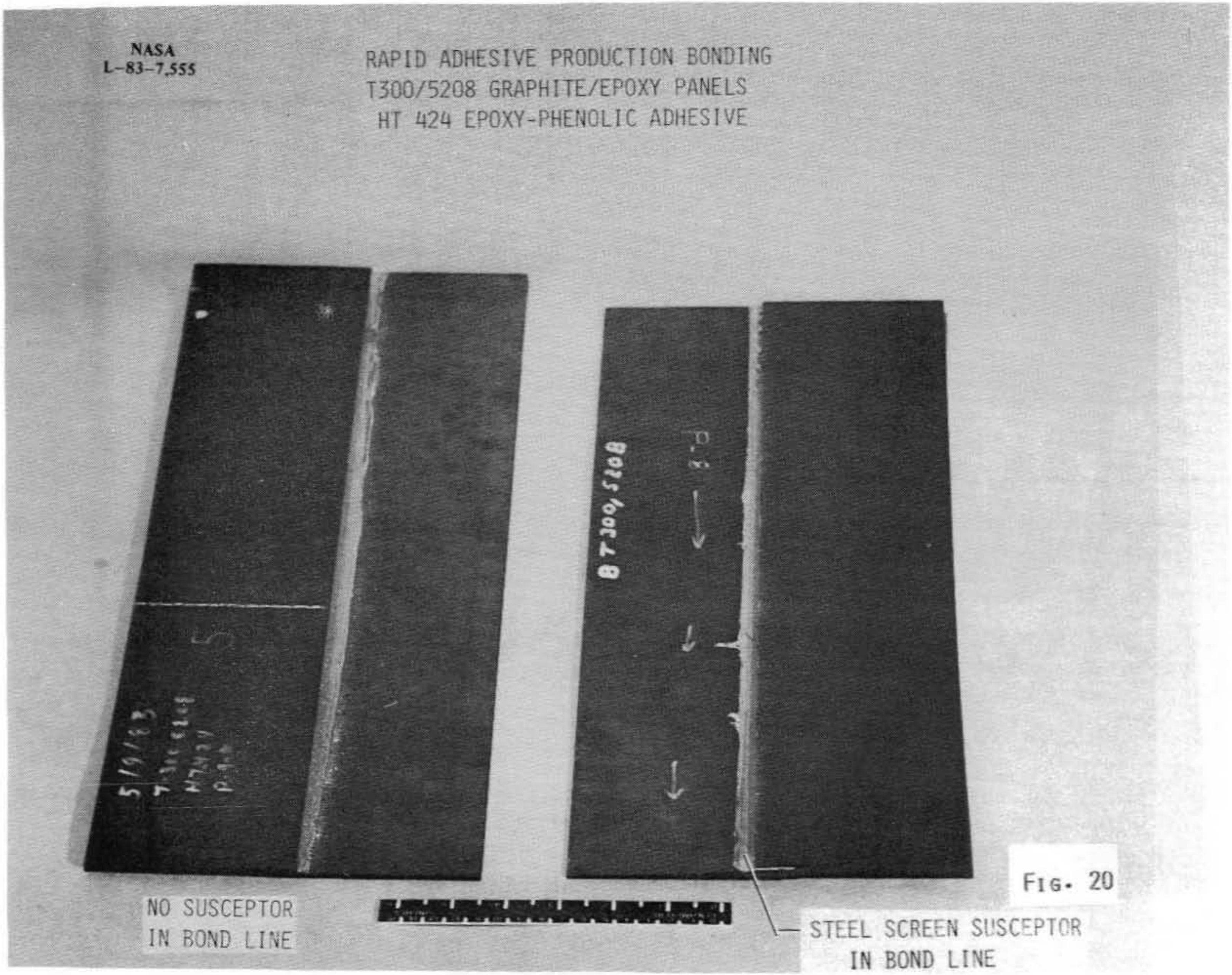
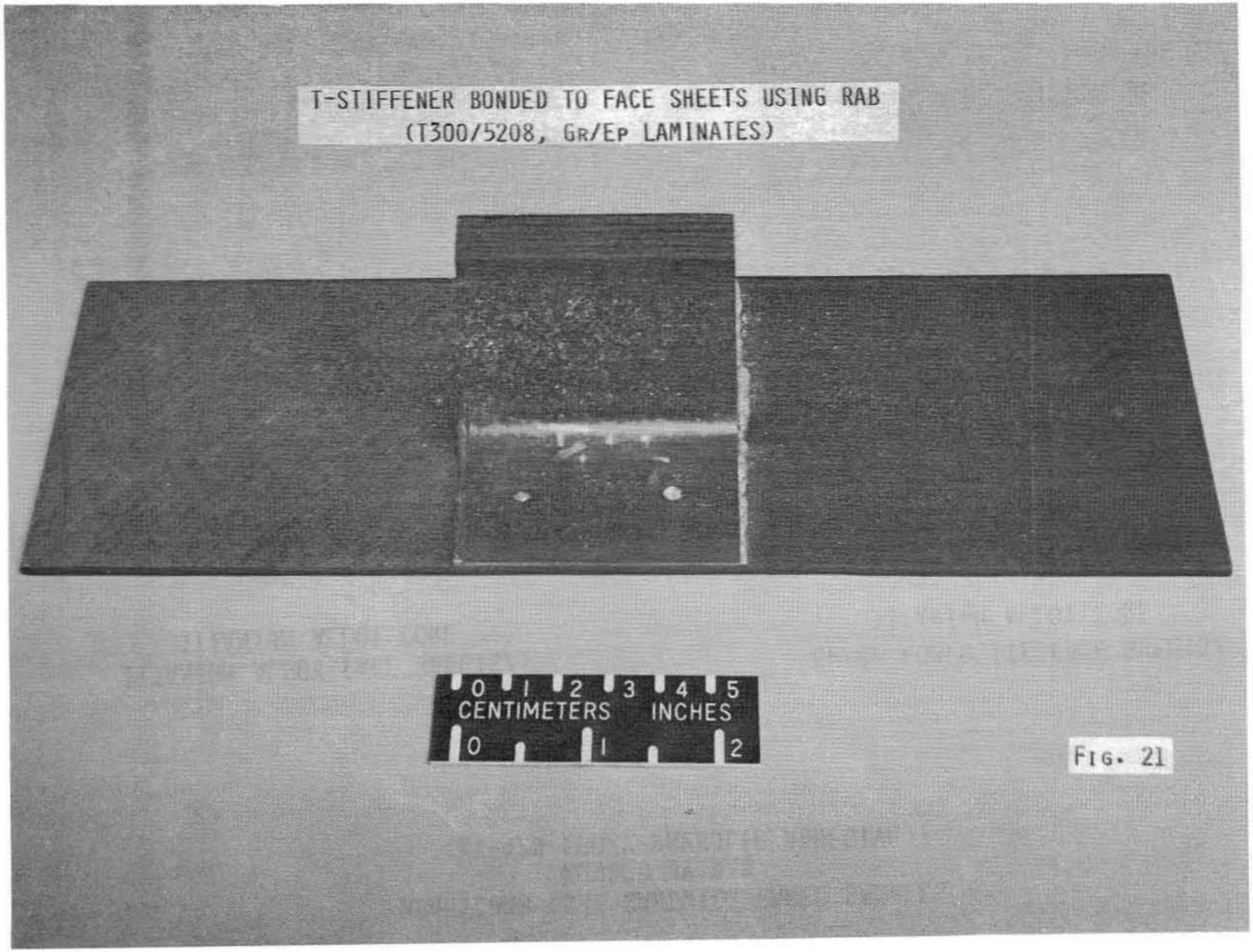

NASA
L-83-7,555
RAPID ADHESIVE PRODUCTION BONDING
T300/5208 GRAPHITE/EPOXY PANELS
HT 424 EPOXY-PHENOLIC ADHESIVE
NO SUSCEPTOR
IN BOND LINE
STEEL SCREEN SUSCEPTOR
IN BOND LINE

FIG. 20

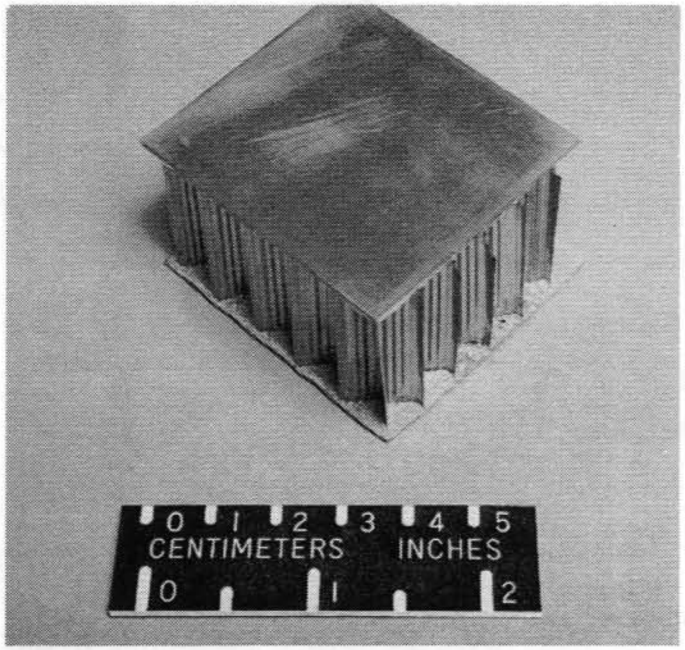


T-STIFFENER BONDED TO FACE SHEETS USING RAB
(T300/5208, GR/EP LAMINATES)

FIG. 21

HONEYCOMB CORE SANDWICH PANEL SAMPLES
BONDED BY RAB
(HT-424 EPOXY-PHENOLIC ADHESIVE)

TITANIUM ALLOY FACE SHEETS/
TITANIUM ALLOY CORE



GR/EP COMPOSITE FACE SHEETS/
TITANIUM ALLOY CORE

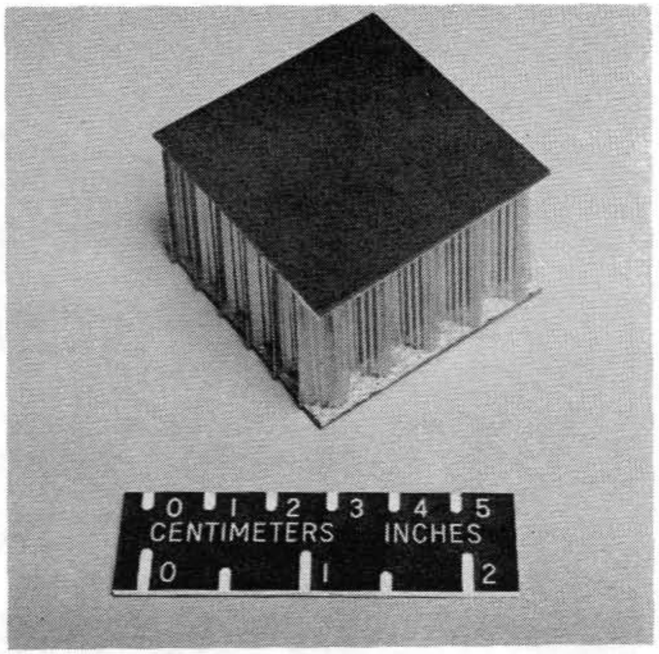
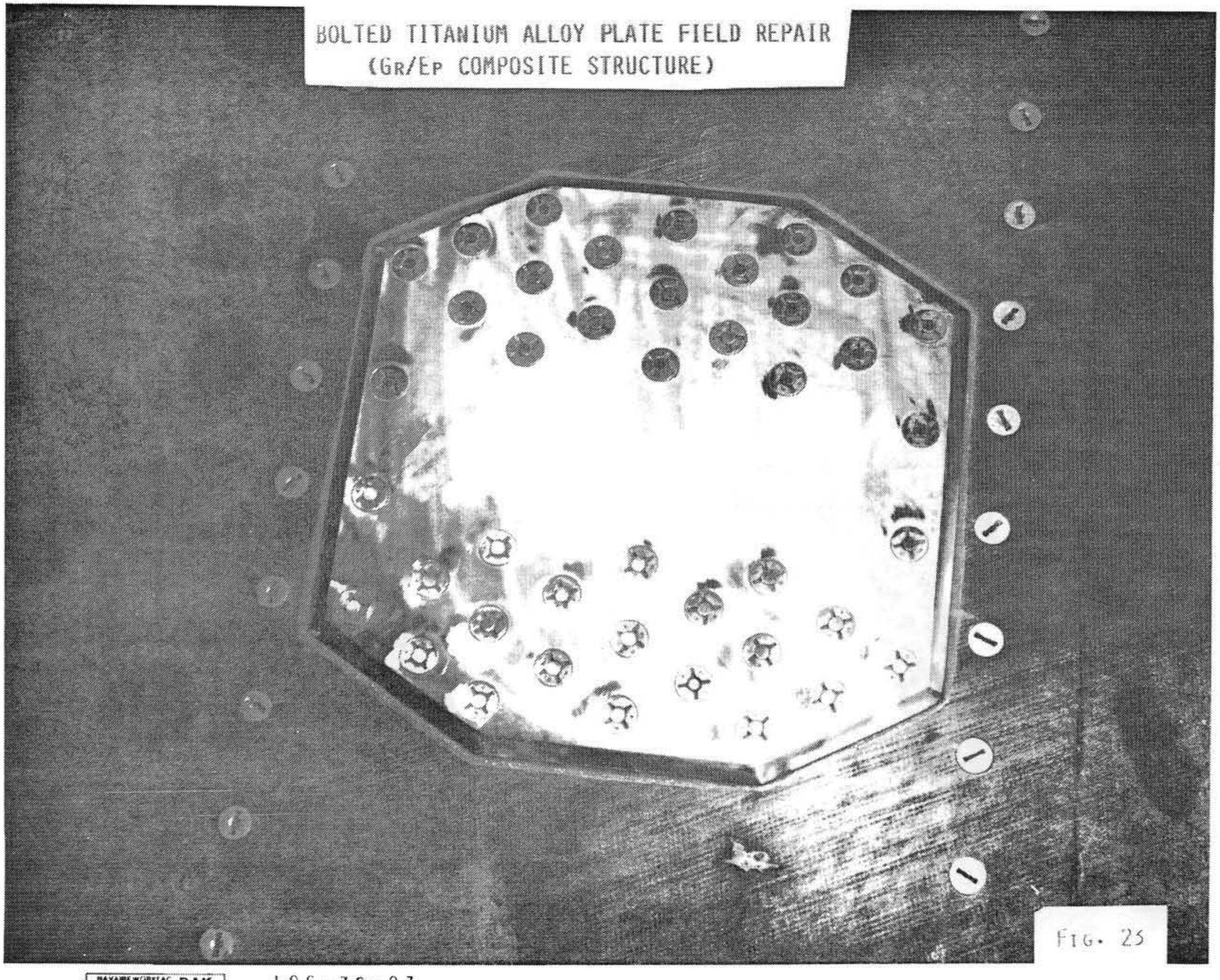


FIG. 22



BOLTED TITANIUM ALLOY PLATE FIELD REPAIR
(GR/EP COMPOSITE STRUCTURE)

FIG. 25

NAVAIREWORKFAC CHERRY POINT, N.C. DAK   106-76-83

RAB REPAIR OF HELICOPTER WINDSCREEN

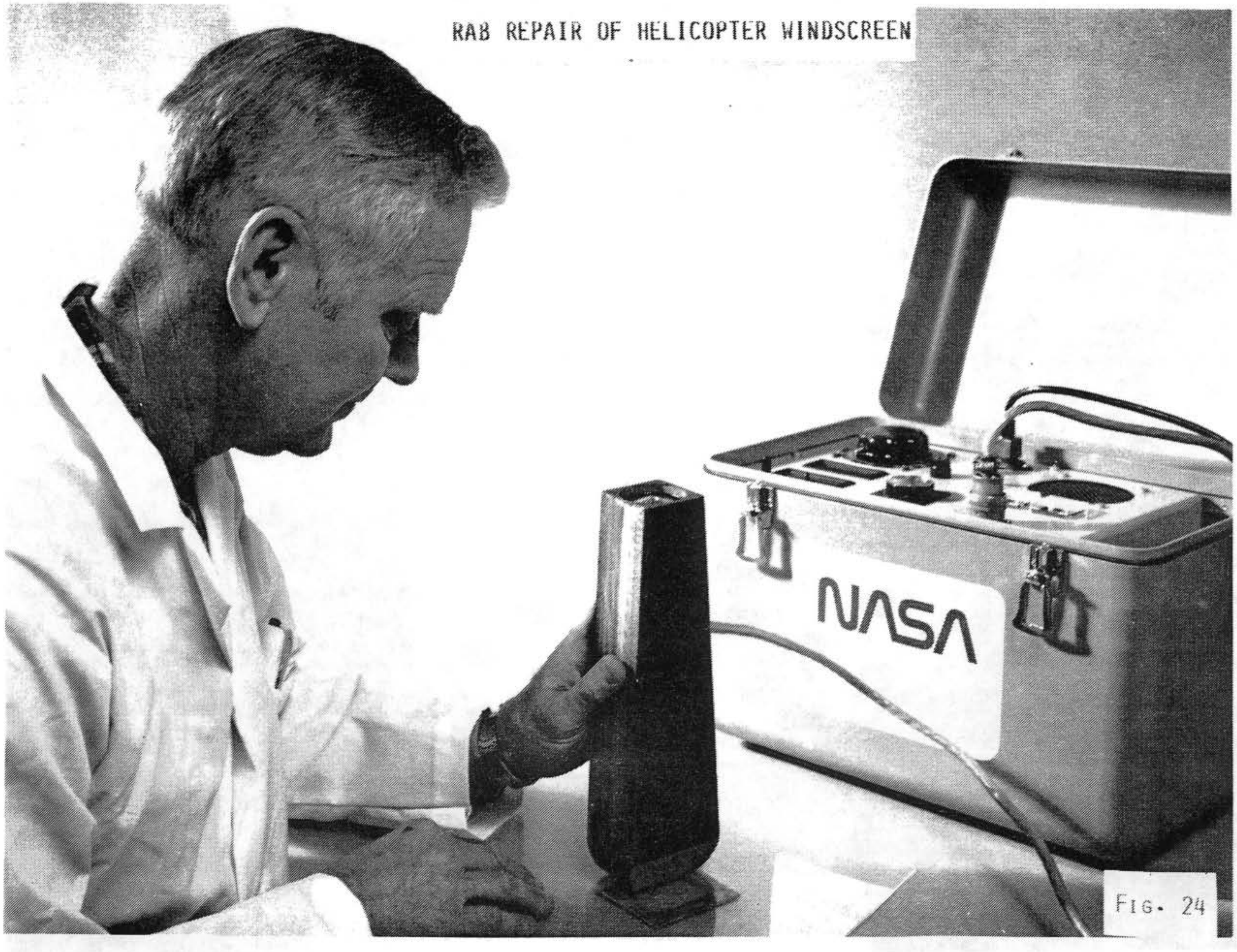


FIG. 24

HELICOPTER WINDSCREENS WITH RAB REPAIRS

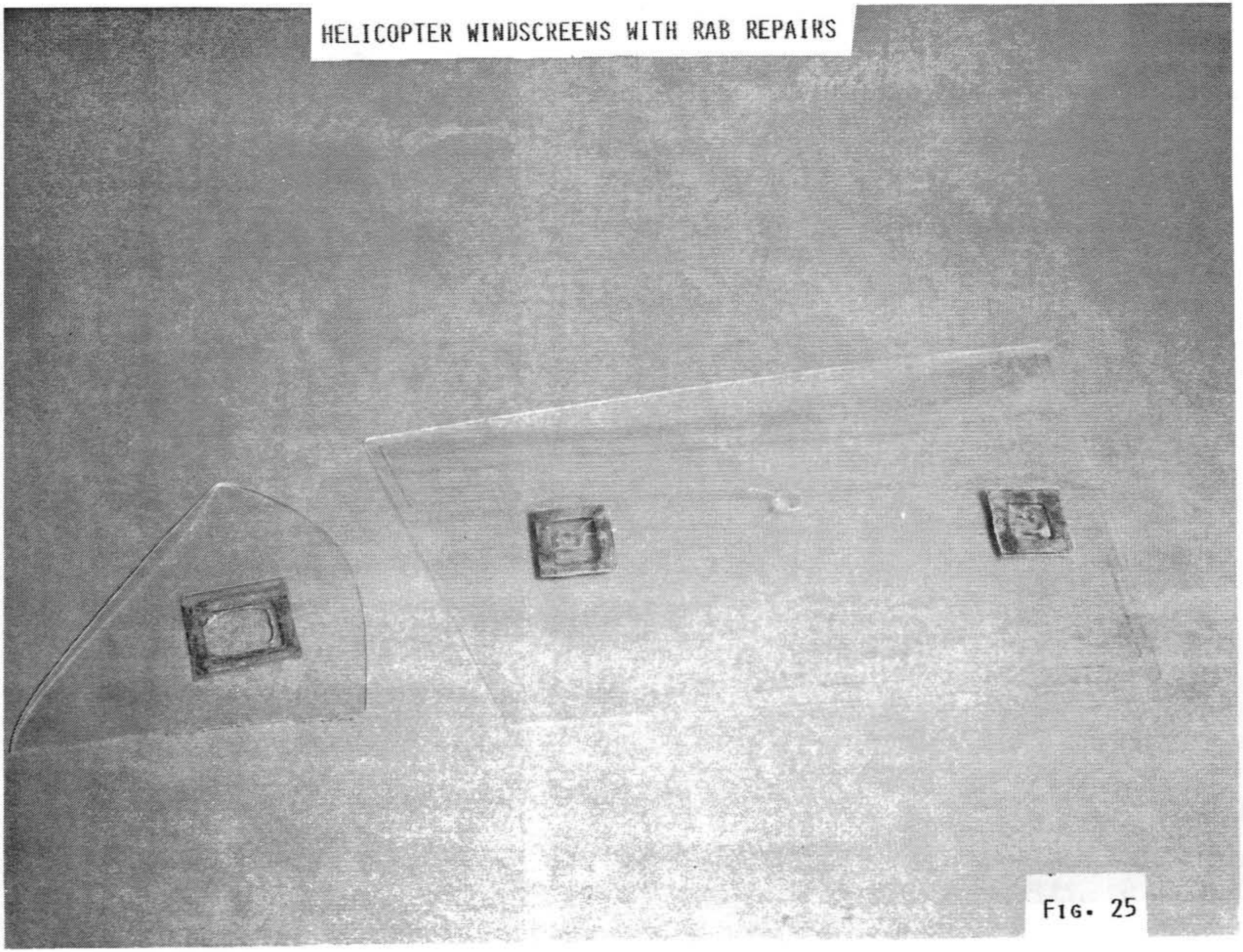
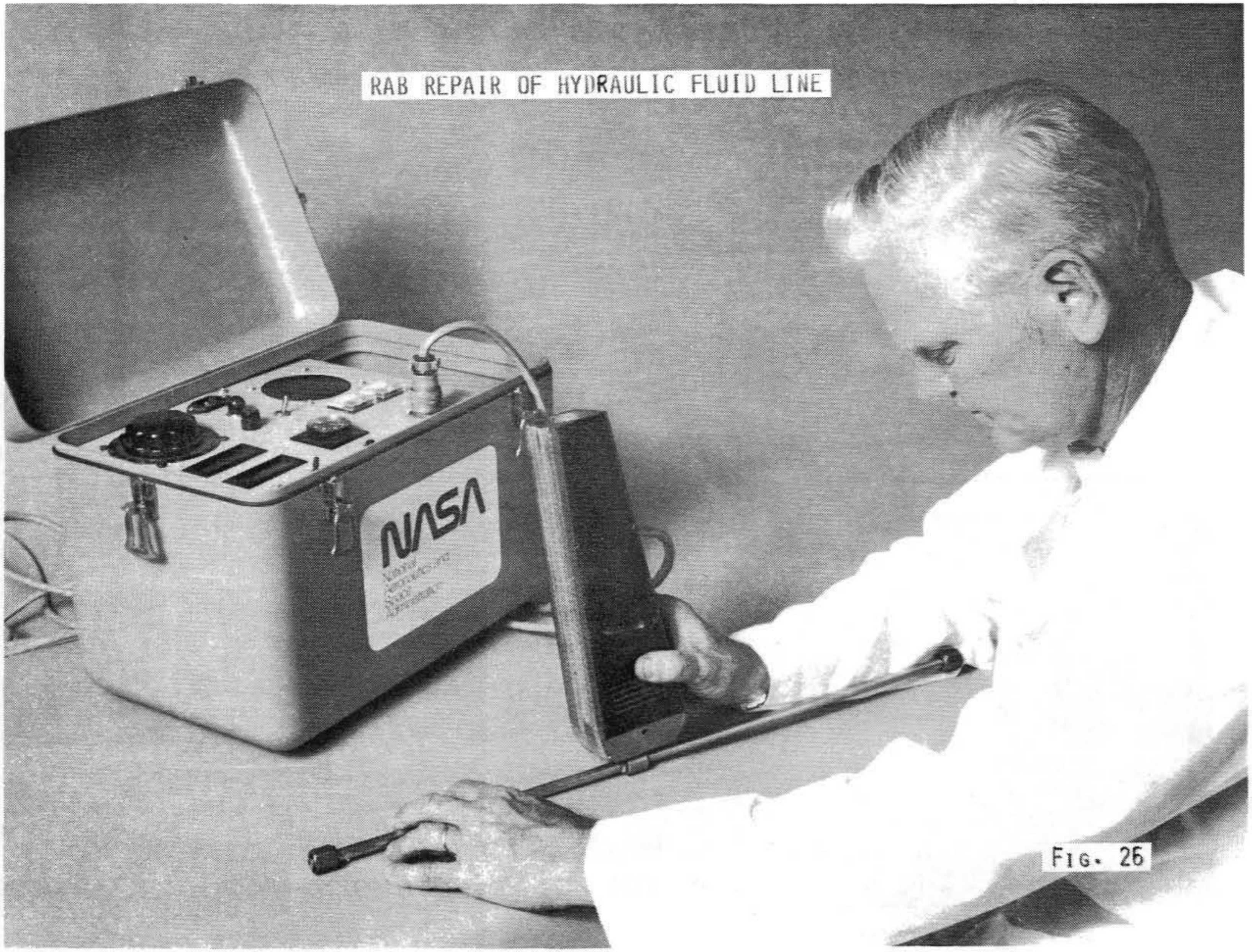
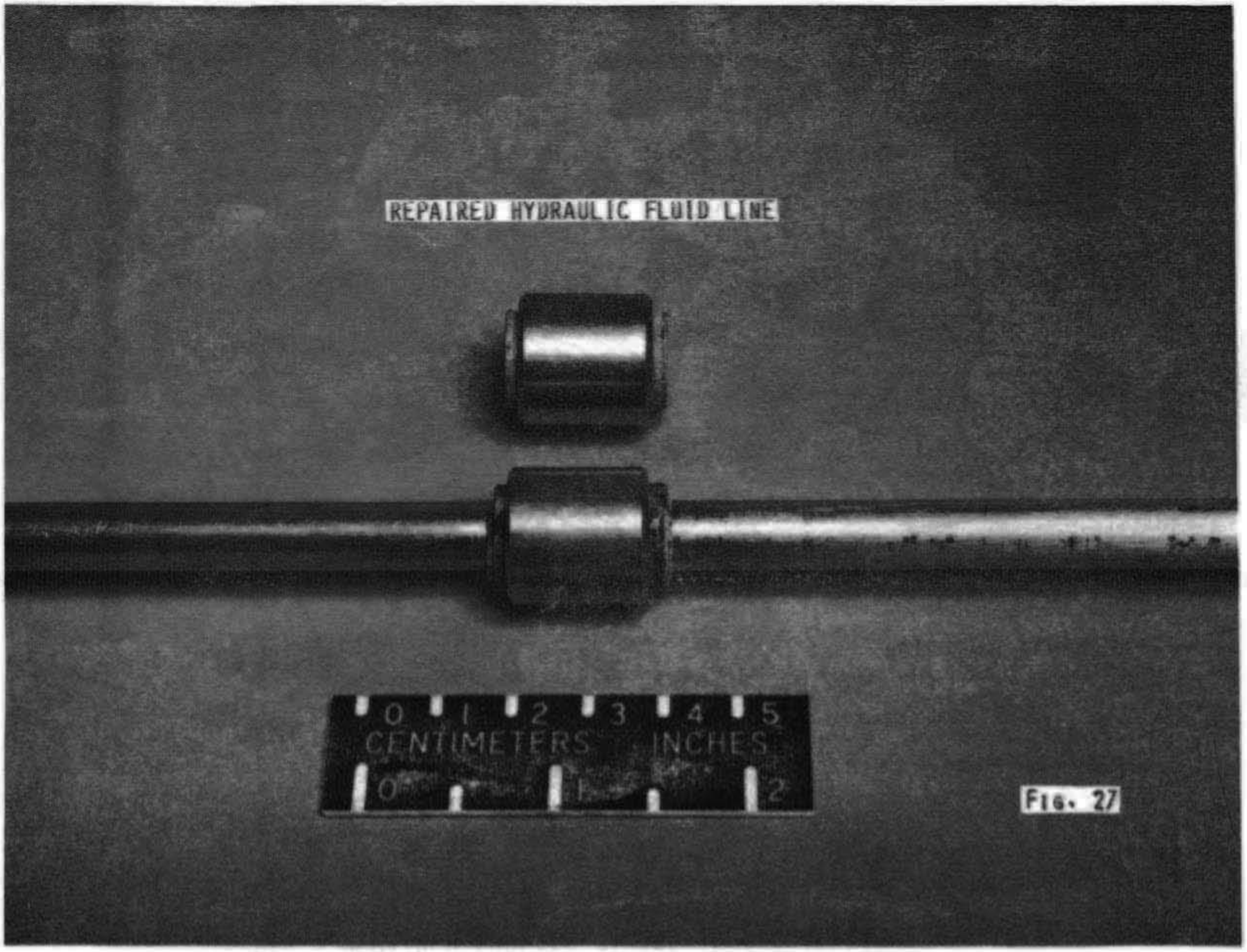


FIG. 25



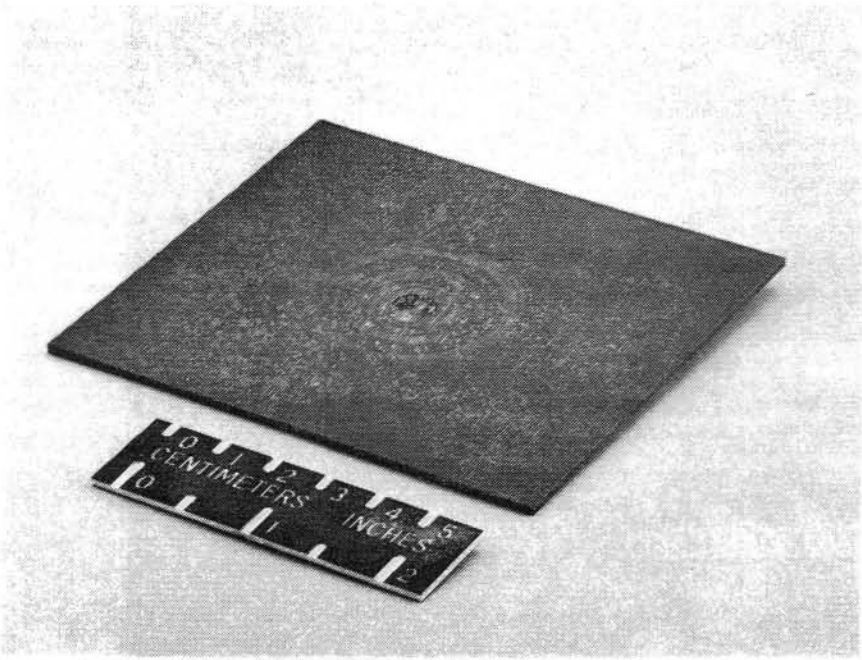
RAB REPAIR OF HYDRAULIC FLUID LINE

FIG. 26


REPAIRED HYDRAULIC FLUID LINE
0 1 2 3 4 5
CENTIMETERS INCHES
0 1 2
FIG. 27

RAB - REPAIRED SURFACE DAMAGE IN A GRAPHITE/EPOXY COMPOSITE PLATE

DAMAGED PLATE



REPAIRED PLATE

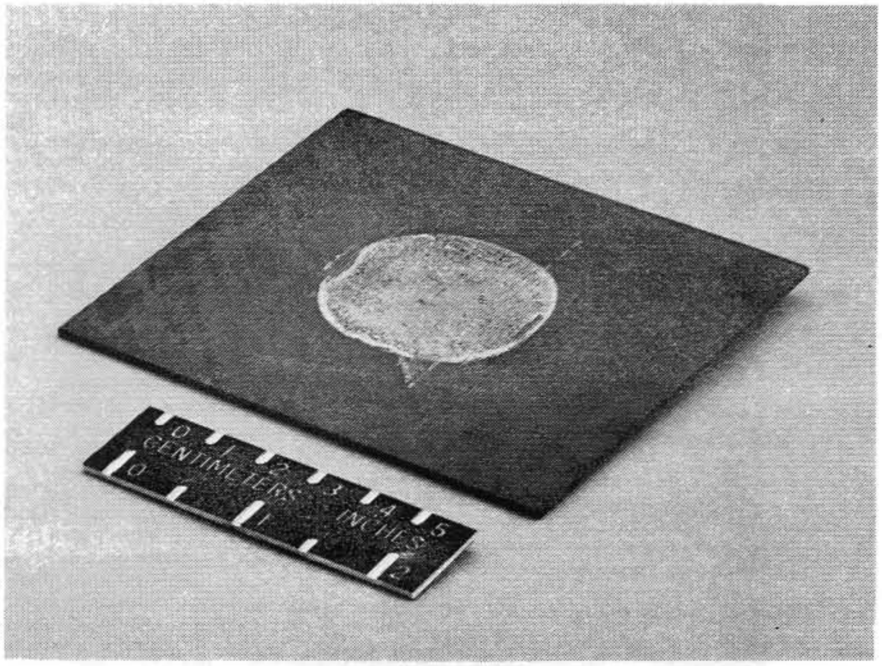


FIG. 28

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86256		

4. Title and Subtitle	5. Report Date
Rapid Adhesive Bonding Concepts	June 1984
	6. Performing Organization Code 505-33-33-01
7. Author(s) B. A. Stein, J. R. Tyeryar, and W. T. Hodges	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes Use of trade names or manufacturers does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

16. Abstract

Adhesive bonding in the aerospace industry typically utilizes autoclaves or presses which have considerable thermal mass. As a consequence, the rates of heatup and cooldown of the bonded parts are limited and the total time and cost of the bonding process is often relatively high. Many of the adhesives themselves do not inherently require long processing times. Bonding could be performed rapidly if the heat was concentrated in the bond lines or at least in the adherends.

Rapid Adhesive Bonding concepts have been developed at the NASA Langley Research Center to utilize induction heating techniques to provide heat directly to the bond line and/or adherends without heating the entire structure, supports, and fixtures of a bonding assembly. Bonding times for specimens can be cut by a factor of 10 to 100 compared to standard press bonding. This paper reviews the development of Rapid Adhesive Bonding for lap shear specimens (per ASTM D1003 and D3163), for aerospace panel bonding, and for field repair needs of metallic and advanced fiber reinforced polymeric matrix composite structures. Details of the equipment and procedures are described for bonding thin sheets, simple geometries, and honeycomb core panels. Test results are presented for a variety of adhesives and for specimens fabricated both with and without heating susceptors in the bond line. Lap shear strengths greater than 4000 psi for titanium adherends and greater than 3000 psi for graphite/epoxy composite adherends are routinely achieved.

The promise of advanced composite and bonded metallic structures for improvements in structural efficiency and cost is limited by current processing and repair technology. Rapid Adhesive Bonding concepts can advance that technology significantly.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Rapid Adhesive Bonding Thermoplastic Adhesives Thermosetting Adhesives Composite Bonding	Unclassified - Unlimited Subject Category - 24

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	73	A04